BMT Fleet Technology Limited

TP 14220E

Effect of Surface Conditions on the Friction Coefficients Measured on Winter Surfaces

Prepared for
Transportation Development Centre
On behalf of
Aerodrome Safety Branch of Civil Aviation
Transport Canada
March 2003

105-06614/

TP 14220E

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by

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by

G. Comfort
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March 2003

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Since some of the accepted measures in the industry are imperial, metric measures are not always used in this report.

Un sommaire français se trouve avant la table des matières.

Transport Canada Transports Canada

PUBLICATION DATA FORM

1. Transport Canada Publication No.
TP 14220E

2. Project No.
5269

3. Recipient's Catalogue No.

4. Title and Subtitle
Effect of Surface Conditions on the Friction Coefficients Measured on Winter Surfaces

5. Publication Date
March 2003

6. Performing Organization Document No.

7. Author(s)
G. Comfort

8. Transport Canada File No.
2450-BP14

9. Performing Organization Name and Address
BMT Fleet Technology Limited
311 Legget Drive
Kanata, Ontario
Canada K2K 1Z8

10. PWGSC File No.
MTB-2-00472

11. PWGSC or Transport Canada Contract No.
T8200-022506/001/MTB

12. Sponsoring Agency Name and Address
Transportation Development Centre (TDC)
800 René Lévesque Blvd. West
Suite 600
Montreal, Quebec
H3B 1X9

13. Type of Publication and Period Covered
Final

14. Project Officer
A. Boccanfuso

15. Supplementary Notes (Funding programs, titles of related publications, etc.)

16. Abstract

Data obtained from the Joint Winter Runway Friction Measurement Program (JWRFMP) were used to investigate the effect of surface conditions on the friction coefficient measured by the Electronic Recording Decelerometer (ERD), the Surface Friction Tester device owned by Transport Canada (TC SFT'79), and the Instrument de Mesure Automatique de la Glissance (IMAG). Two types of analyses were conducted:

1. Analyses for individual surfaces – where possible, the friction coefficients obtained from the devices were compared to the guideline Canadian Runway Friction Index (CRFI) given in the Aeronautical Information Publication (AIP)
2. Correlations among the devices

The results varied from device to device and surface to surface, which makes it difficult to infer general conclusions.

This project should be followed up with more detailed quantitative analyses to investigate issues such as the variability among the results for different surfaces, and the degree of confidence that one could have in friction coefficients inferred solely from surface descriptions, in comparison to data obtained with friction-measuring devices.

17. Key Words
Joint Winter Runway Friction Measurement Program, JWRFMP, Canadian Runway Friction Index, CRFI, friction coefficient, friction-measuring device, correlation

18. Distribution Statement
Limited number of copies available from the Transportation Development Centre

19. Security Classification (of this publication)
Unclassified

20. Security Classification (of this page)
Unclassified

21. Declassification (date)
—

22. No. of Pages
xvi, 64, apps

23. Price
Shipping/ Handling

Canada

Transports Canada Transport Canada

FORMULE DE DONNÉES POUR PUBLICATION

1. N° de la publication de Transports Canada
TP 14220E

2. N° de l'étude
5269

3. N° de catalogue du destinataire

4. Titre et sous-titre
Effect of Surface Conditions on the Friction Coefficients Measured on Winter Surfaces

5. Date de la publication
Mars 2003

6. N° de document de l'organisme exécutant

7. Auteur(s)
G. Comfort

8. N° de dossier - Transports Canada
2450-BP14

9. Nom et adresse de l'organisme exécutant
BMT Fleet Technology Limited
311 Legget Drive
Kanata, Ontario
Canada K2K 1Z8

10. N° de dossier - TPSGC
MTB-2-00472

11. N° de contrat - TPSGC ou Transports Canada
T8200-022506/001/MTB

12. Nom et adresse de l'organisme parrain
Centre de développement des transports (CDT)
800, boul. René-Lévesque Ouest
Bureau 600
Montréal (Québec)
H3B 1X9

13. Genre de publication et période visée
Final

14. Agent de projet
A. Boccanfuso

15. Remarques additionnelles (programmes de financement, titres de publications connexes, etc.)

16. Résumé

Des données recueillies au cours du Programme conjoint de recherche sur la glissance des chaussées aéronautiques l'hiver (PCRGCAH) ont été utilisées pour étudier l'effet de l'état de la surface sur le coefficient de frottement mesuré au moyen du décéléromètre électronique (ERD, pour *Electronic Recording Decelerometer*), du glissancemètre de Transports Canada (TC SFT'79) et de l'Instrument de mesure automatique de la glissance (IMAG). Deux types d'analyses ont été effectuées :

1. Analyses portant sur chaque surface – là où c'était possible, les coefficients de frottement obtenus à l'aide des appareils de mesure ont été comparés aux mesures du Coefficient canadien de frottement sur piste (CRFI, pour *Canadian Runway Friction Index*) données dans la Publication d'information aéronautique (AIP, pour *Aeronautical Information Publication*).
2. Analyses de corrélation entre les appareils de mesure.

Les résultats variaient d'un appareil à l'autre et d'une surface à l'autre, ce qui a empêché de tirer des conclusions générales.

Comme suite à ces travaux, il y aurait lieu d'effectuer des analyses quantitatives plus détaillées afin de mieux cerner des questions comme la variabilité des résultats obtenus sur divers états de piste, et le niveau de confiance que l'on peut avoir dans des coefficients de frottement déduits uniquement des caractéristiques de la piste, par opposition à des coefficients de frottement mesurés par des appareils.

17. Mots clés
Programme conjoint de recherche sur la glissance des chaussées aéronautiques l'hiver, PCRGCAH, Coefficient canadien de frottement sur piste, CRFI, coefficient de frottement, appareil de mesure du frottement, corrélation

18. Diffusion
Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

19. Classification de sécurité (de cette publication)	20. Classification de sécurité (de cette page)	21. Déclassification (date)	22. Nombre de pages	23. Prix
Non classifiée	Non classifiée	—	xvi, 64, ann.	Port et manutention

ACKNOWLEDGEMENTS

The project was monitored by Angelo Boccanfuso of Transport Canada. He is thanked for his input over the course of the project.

Alice Krol, of the Aerodrome Safety Branch of Transport Canada, provided technical direction in several meetings and telephone calls. She is thanked for her suggestions.

Brahim Djimet carried out the database searches used for these analyses.

EXECUTIVE SUMMARY

Testing has been under way at North Bay and elsewhere since 1996 as part of the Joint Winter Runway Friction Measurement Program (JWRFMP). The main research objectives are to:

- Compare friction readings from various devices
- Evaluate the relationship between ground vehicle and aircraft friction coefficients

The results of this testing have led to the generation of a large information database regarding friction coefficients on winter surfaces.

The general objective of this project was to investigate the effect of surface conditions on friction coefficients. The work comprised two general parts: analyses for individual surfaces and correlation analyses.

Analyses for Individual Surfaces

This work investigated the friction coefficients measured for various surface types such as ice, snow, packed snow, and dry and wet pavement. Three devices were analyzed:

1. Electronic Recording Decelerometer (ERD)
2. Transport Canada's Surface Friction Tester (TC SFT'79)
3. Instrument de Mesure Automatique de la Glissance (IMAG)

The following issues were examined:

- Range and distribution of friction coefficient values by surface and friction-measuring device
- Effect of surface temperature
- Effect of snow depth for surfaces with loose snow

The results were compared to the Canadian Runway Friction Index (CRFI) guidelines given in the Aeronautical Information Publication (AIP). The results varied from device to device and from surface to surface, which makes it difficult to infer general conclusions. It was, however, commonly observed that the ranges of values observed in the JWRFMP were larger than those given in the AIP.

Correlation Analyses

This work evaluated the effects of surface conditions on correlations between measurements recorded by the above devices.

Again, the results varied from device to device and from surface to surface, which makes it difficult to infer general conclusions. However, it was noted that:

- ERD readings on contaminated surfaces were generally higher and more scattered on contaminated surfaces than those for the TC SFT'79 and the IMAG. This probably reflects the fact that the ERD is a locked-wheel test.
- TC SFT'79 and the IMAG showed good correlation for all surfaces.

Recommendations

This was an exploratory project to investigate general trends and relationships. The results obtained here should be followed up with more detailed quantitative analyses to investigate issues such as:

- Variability among the results for different surfaces.
- Degree of confidence that one could have in friction coefficients inferred solely from surface descriptions, in comparison to data obtained with friction-measuring devices.

SOMMAIRE

Introduction

Depuis 1996, des essais ont lieu dans le cadre du Programme conjoint de recherche sur la glissance des chaussées aéronautiques l'hiver (PCRGCAH). Ces essais, qui ont lieu à North Bay et ailleurs dans le monde, ont comme grands objectifs:

- de comparer les valeurs de frottement obtenues à l'aide de divers appareils de mesure
- d'évaluer la relation entre les coefficients de frottement établis à l'aide de véhicules au sol et d'aéronefs

Ces essais ont permis d'accumuler une imposante base de données concernant les coefficients de frottement sur des surfaces contaminées par des précipitations hivernales.

L'objectif principal de ce projet était d'étudier l'effet de l'état de la surface sur les coefficients de frottement mesurés sur celle-ci. Les travaux comportaient deux volets: des analyses portant sur chaque surface et des analyses de corrélation entre les appareils de mesure.

Analyses portant sur chaque surface

Ce travail a consisté à analyser les coefficients de frottement mesurés sur divers états de piste: piste couverte de glace, de neige et de neige compactée, piste sèche et piste mouillée. Trois appareils ont été utilisés:

1. le décéléromètre électronique (ERD, pour *Electronic Recording Decelerometer*)
2. le glissancemètre de Transports Canada (TC SFT'79)
3. l'Instrument de mesure automatique de la glissance (IMAG)

Les questions suivantes ont été examinées:

- Étendue et distribution des valeurs du coefficient de frottement selon la surface et l'appareil de mesure
- Effet de la température de la surface
- Effet de l'épaisseur de la neige, dans le cas de surfaces couvertes de neige folle

Les résultats ont été mis en relation avec les mesures du Coefficient canadien de frottement sur piste (CRFI, pour *Canadian Runway Friction Index*) contenues dans la Publication d'information aéronautique (AIP, pour *Aeronautical Information Publication*). Comme les résultats variaient d'un appareil à l'autre et d'une surface à l'autre, il n'a pas été possible de tirer de conclusion générale. On a toutefois couramment observé que la gamme des valeurs issues du PCRGCAH était plus étendue que celle des valeurs données par l'AIP.

Analyses de corrélation

Cette partie du travail a consisté à évaluer les effets de l'état de la surface sur la corrélation entre les mesures enregistrées par les divers appareils susmentionnés.

Encore une fois, les résultats variaient d'un appareil à l'autre et d'une surface à l'autre, ce qui n'a pas permis de tirer de conclusion générale. Il a toutefois été possible de noter ce qui suit:

- Sur les surfaces contaminées, les lectures faites par l'ERD étaient généralement supérieures à celles obtenues à l'aide du glissancemètre de TC et de l'IMAG, et elles étaient aussi plus dispersées. Cela est probablement attribuable au fait que l'ERD est un appareil qui prend ses mesures avec la roue bloquée.
- Le glissancemètre de TC et l'IMAG ont affiché une bonne corrélation pour toutes les surfaces.

Recommandations

Ce projet à caractère exploratoire visait à cerner des tendances et des liens généraux. Les résultats obtenus ici devraient faire l'objet d'analyses quantitatives plus détaillées afin de clarifier des questions comme:

- la variabilité entre les résultats obtenus pour différents états de piste.
- le niveau de confiance que l'on peut avoir dans les coefficients de frottement déduits uniquement des caractéristiques de la piste, par opposition à des coefficients de frottement mesurés par des appareils.

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GLOSSARY OF TERMS

AIP	Aeronautical Information Publication
CRFI	Canadian Runway Friction Index
ERD	Electronic Recording Decelerometer
IMAG	Instrument de Mesure Automatique de la Glissance (French acronym for friction-measuring device manufactured by the French Civil Aviation Authority)
IRV	IRFI Reference Vehicle
IRFI	International Runway Friction Index
JWRFMP	Joint Winter Runway Friction Measurement Program
TC SFT'79	Surface Friction Tester device owned by Transport Canada

1. INTRODUCTION

1.1 Background

Testing has been under way at North Bay and elsewhere since 1996 as part of the Joint Winter Runway Friction Measurement Program (JWRFMP). The main research objectives are as follows:

- to compare friction readings from various devices
- to evaluate the relationship between ground vehicle and aircraft friction coefficients

The results of this testing have led to the generation of a large information database [1] regarding friction coefficients on winter surfaces.

1.2 Objective

The general objective of this project was to investigate the effect of surface conditions on friction coefficients. The work comprised two general parts:

[1] Analyses for Individual Surfaces – This work investigated the friction coefficients measured for various surface types such as ice, compacted snow, and others. The results were also compared to the Canadian Runway Friction Index (CRFI) guidelines given in the Aeronautical Information Publication (AIP) [2]. The work investigated the following issues:

(a) Range and distribution of values by surface and friction-measuring device – the surfaces evaluated included those given in the AIP [2]. Three devices were analyzed:
  i. Electronic Recording Decelerometer (ERD)
  ii. Transport Canada's Surface Friction Tester (TC SFT'79)
  iii. Instrument de Mesure Automatique de la Glissance (IMAG)
(b) Effect of surface temperature
(c) Effect of snow depth for surfaces with loose snow

[2] Correlation Analyses – This work evaluated the effects of surface conditions on correlations between measurements recorded by the above devices.

2. METHOD AND DATABASE SEARCH PARAMETERS

2.1 Overall Summary

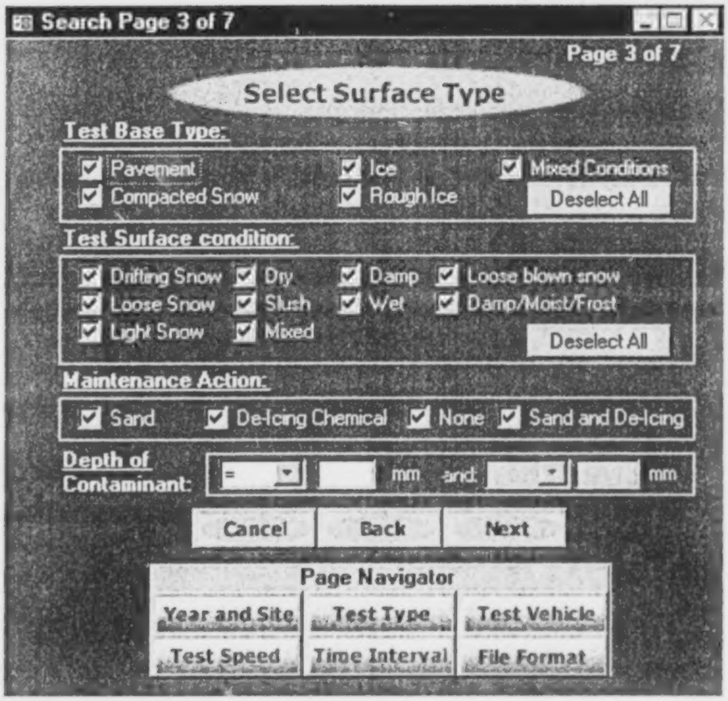
Database search parameters were specified as follows:

- Year and site – All years and sites were included in all searches to maximize the size of the data set.
- Speed – All speeds were included in all searches. This was done as previous analyses (e.g., [3]) have shown that friction coefficients on winter surfaces are not greatly dependent on speed. The data set was maximized by including all speeds.
- Surface and base conditions – Several cases were investigated as described in section 2.2.
- Devices – The analyses were limited to the friction coefficients measured by the ERD, the TC SFT'79 and the IMAG (section 2.3). The IMAG was investigated rather than the IRFI Reference Vehicle (IRV) as the IMAG was tested over a longer time span during the JWRFMP.
- Maintenance action – In most cases, the searches were made for surfaces that had not been treated with any maintenance action. However, a few searches were made for sanded ice (see section 2.2).
- Time interval between individual friction readings – All readings were included. The results were not partitioned by time interval.
- Track section on which the average friction coefficient is computed – The analyses were done using average friction coefficients for the whole track section, as opposed to 100 m sections (which is the other option in the search wizard). This selection was made because it maximized the size of the data set, as only "whole track" data were recorded during the early years of the JWRFMP.

2.2 Surfaces Evaluated

2.2.1 Surfaces Evaluated

The search wizard in the database [1] allows the user to specify various combinations of base and surface conditions. See Figure 2.1. Efforts were made to select the same surfaces given in the AIP [2] (Figure 2.2) to the extent possible. The surfaces evaluated are listed in Table 2.1.



Search Page 3 of 7

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Select Surface Type

Test Base Type:

☑ Pavement ☑ Ice ☑ Mixed Conditions
☑ Compacted Snow ☑ Rough Ice

Test Surface condition:

☑ Drifting Snow ☑ Dry ☑ Damp ☑ Loose blown snow
☑ Loose Snow ☑ Slush ☑ Wet ☑ Damp/Moist/Frost
☑ Light Snow ☑ Mixed

Maintenance Action:

☑ Sand ☑ De-Icing Chemical ☑ None ☑ Sand and De-Icing

Depth of Contaminant: = mm and mm

Deselect All
Deselect All
Cancel
Back
Next
Page Navigator
Year and Site
Test Type
Test Vehicle
Test Speed
Time Interval
File Format

Figure 2.1: Selectable Base and Surface Conditions in the Database Search Wizard [1]

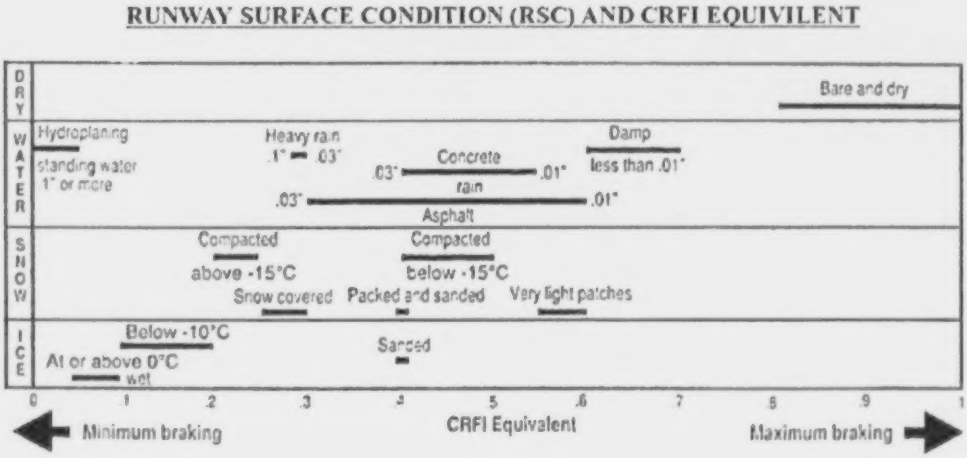
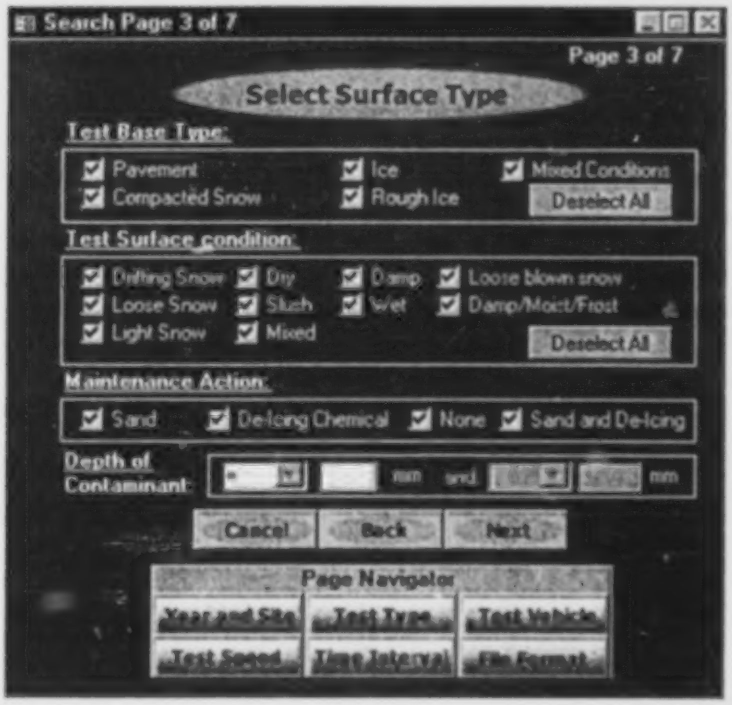


Figure 2.2: CRFIs Given in the AIP for Various Surfaces [2]



Search Page 3 of 7
Page 3 of 7
Select Surface Type
Deselect All
Deselect All
Cancel
Back
Next
Page Navigator
Year and Site
Test Type
Test Vehicle
Test Speed
Time Interval
File Format

Test Base Type:

☑ Pavement ☑ Ice ☑ Mixed Conditions
☑ Compacted Snow ☑ Rough Ice

Test Surface condition:

☑ Drifting Snow ☑ Dry ☑ Damp ☑ Loose blown snow
☑ Loose Snow ☑ Slush ☑ Wet ☑ Damp/Moist/Frost
☑ Light Snow ☑ Mixed

Maintenance Action:

☑ Sand ☑ De-Icing Chemical ☑ None ☑ Sand and De-Icing

Depth of Contaminant: mm and mm

Figure 2.1: Selectable Base and Surface Conditions in the Database Search Wizard [1]

RUNWAY SURFACE CONDITION (RSC) AND CRFI EQUIVILENT

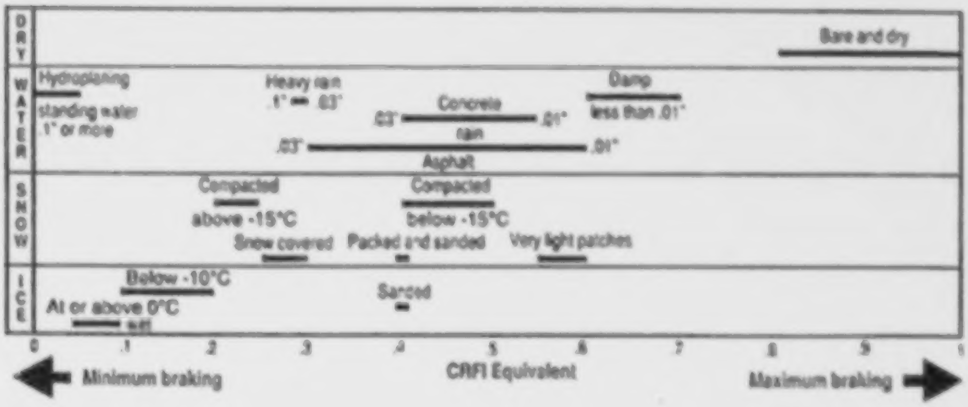


Figure 2.2: CRFIs Given in the AIP for Various Surfaces [2]

Table 2.1: Database Search Summary

Surface	ERD	TC SFT'79 – all Cs[1]	TC SFT'79 – C3[1]	IMAG – All Cs[1]	IMAG C3C7[1]
Bare Ice: • >= 0°C • 0°C to -10°C • <= -10°C	√	√	√	√	√
Bare Ice and Rough Ice: • >= 0°C • 0°C to -10°C • <= -10°C	√	√	√	√	√
Sanded Bare Ice: • >= 0°C • 0°C to -10°C • <= -10°C	√	√	√	√	√
Sanded Bare Ice and Rough Ice: • >= 0°C • 0°C to -10°C • <= -10°C	√	√	No data	√	√
Bare Packed Snow: • > -15°C • <= -15°C	√	√	√	√	√
Snow on Pavement: • >= 0°C • 0°C to -10°C • <= -10°C	√	√	√	√	√
Snow on Ice: • >= 0°C • 0°C to -10°C • <= -10°C	√	√	√	√	√
Snow on Rough Ice: • >= 0°C • 0°C to -10°C • <= -10°C	√	√	√	√	√
Snow on Packed Snow: • > -15°C • <= -15°C	√	√	√	√	√
Bare Pavement	√	√	√	√	√
Wet or Damp Pavement: • Wet Pavement • Damp Pavement	√ √		√		√
Slush on any base	√	√	√	√	√

1: Legend (See Table 2.2 for a description of the configurations below):

- TC SFT'79 – all Cs: all configurations for the TC SFT'79
- TC SFT'79 – C3: configuration 3 for the TC SFT'79
- IMAG – all Cs: all configurations for the IMAG
- IMAG – C3C7: configurations 3 and 7 for the IMAG

2.2.2 Effect of Snow Depth

The friction coefficients for snow-covered surfaces were also evaluated, although these are not included in the AIP guideline (Figure 2.2). It is well known that snow depth affects measured friction coefficients. Consequently, the effect of snow depth was investigated to assess the most appropriate way to partition the data set.

The effect of snow depth is shown in Figures 2.3 to 2.9 for the devices evaluated. The devices that were evaluated and corresponding configurations are described in section 2.3.

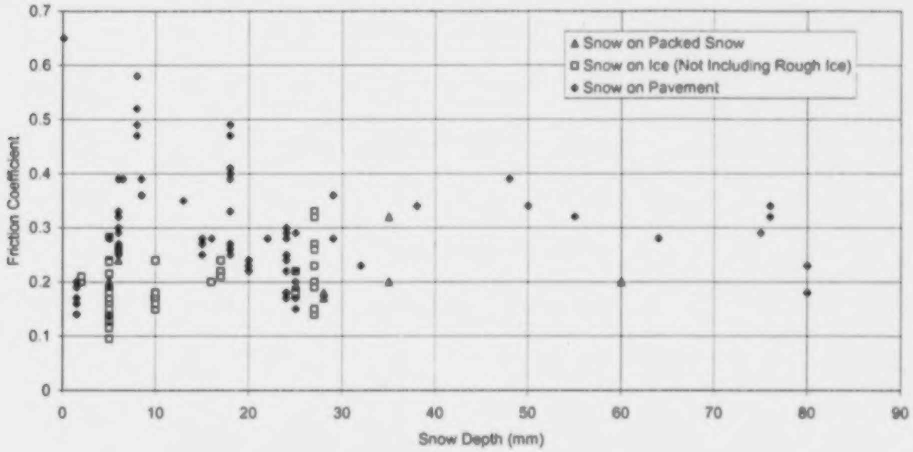


Figure 2.3: Effect of Snow Depth on ERD Readings

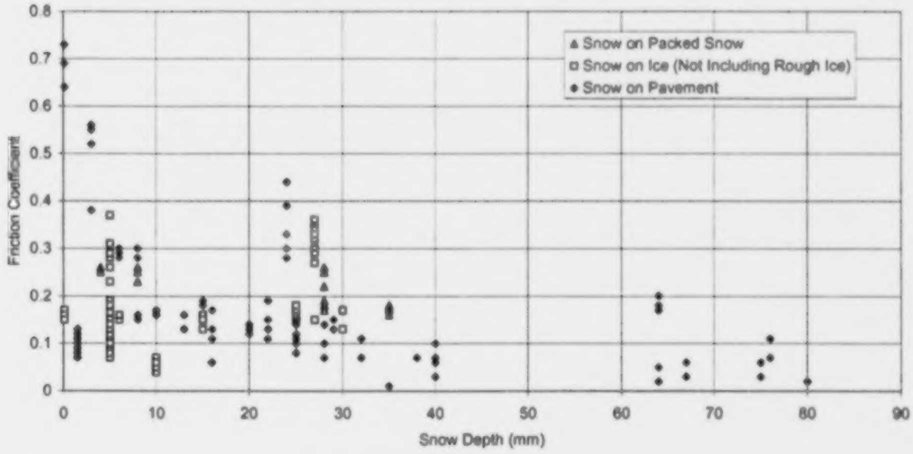


Figure 2.4: Effect of Snow Depth on TC SFT'79 Readings (All Configurations)

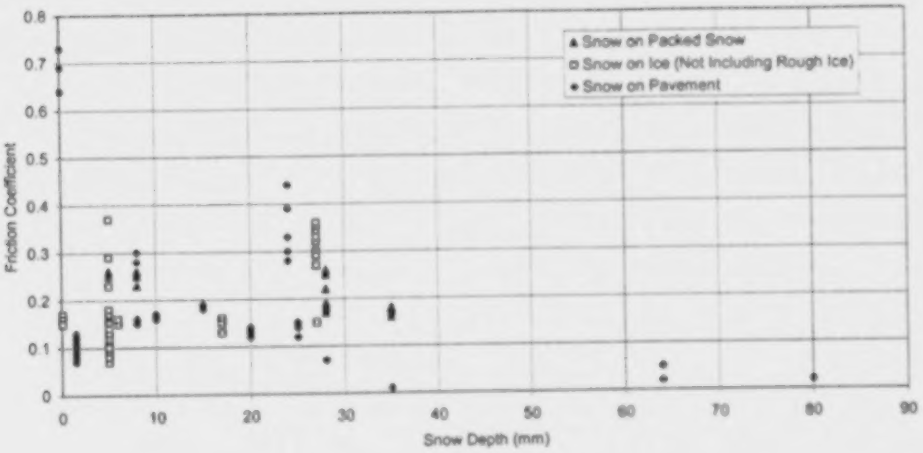


Figure 2.5: Effect of Snow Depth on TC SFT'79 Readings (Configuration 3)

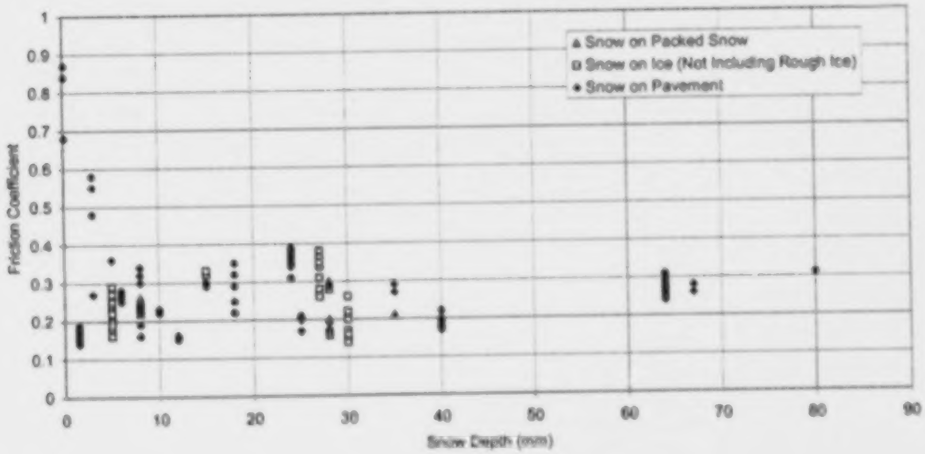


Figure 2.6: Effect of Snow Depth on IMAG Force Readings (All Configurations)

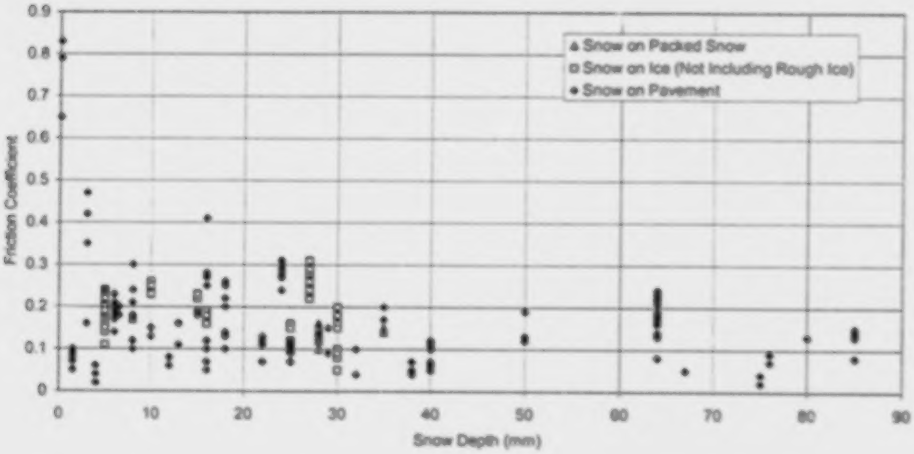


Figure 2.7: Effect of Snow Depth on IMAG Torque Readings (All Configurations)

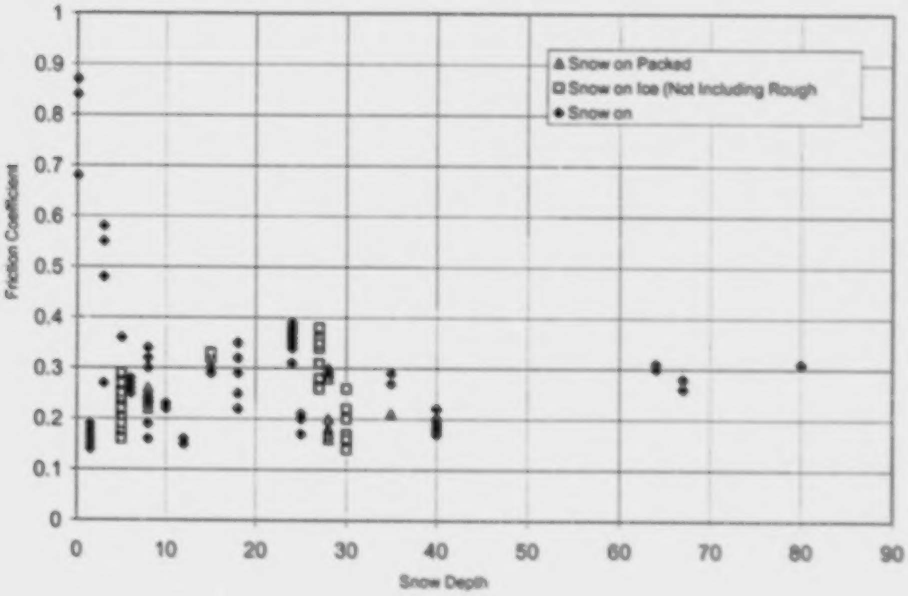


Figure 2.8: Effect of Snow Depth on IMAG Force Readings (Configurations 3 and 7)

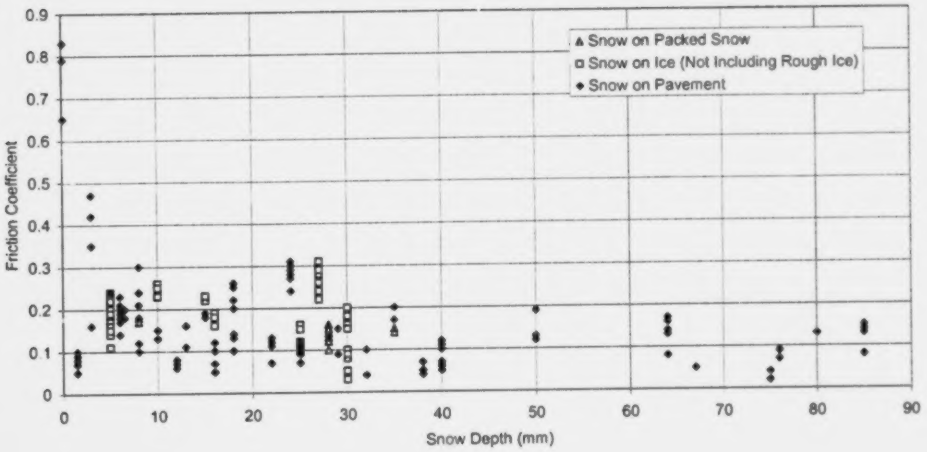


Figure 2.9: **Effect of Snow Depth on IMAG Torque Readings (Configurations 3 and 7)**

The effect of snow depth depends on the device and surface under consideration as summarized below:

(1) ERD (shown in Figure 2.3)

a. Snow on Ice – Although the relationship is scattered, the ERD reading tends to increase with increasing snow depth. This probably reflects an increasing amount of contaminant drag as the snow depth is increased.

b. Snow on Packed Snow – Only a few data points are available, which makes it difficult to define trends.

c. Snow on Pavement – The ERD reading tends to level off (thus becoming independent of snow depth) at depths exceeding 10-20 mm. At lower snow depths, the ERD reading varies significantly from values near those expected for bare pavement to those expected for bare packed snow. This range may reflect differences in snow coverage over the pavement. Alternatively, it may indicate that the vehicle wheels were breaking through the snow cover to reach bare pavement during friction measurements.

(2) TC SFT'79 (shown in Figures 2.4 and 2.5)

a. Snow on Ice – Although the relationship is scattered, the friction coefficient tends to increase with increasing snow depth. This probably reflects an increasing amount of contaminant drag as the snow depth is increased.

b. Snow on Packed Snow – The friction coefficient tends to decrease with increasing snow depth for both cases evaluated (i.e., all configurations of the TC SFT'79, and only configuration 3). This trend may reflect increased bonding between the snow on the surface to the packed snow base for deeper depths, which would cause the TC SFT'79 to tend to see a snow surface at deeper snow depths.

c. Snow on Pavement – The TC SFT'79 reading decreases exponentially as the snow depth is increased. As for the "snow on packed snow" case above, this trend may reflect increased bonding between the snow on the surface to the pavement base for deeper depths. This would cause the TC SFT'79 to tend to see a snow surface at deeper snow depths.

(3) IMAG (shown in Figures 2.6 to 2.9)

a. Snow on Ice – As for the ERD and the TC SFT'79, the friction coefficient tends to increase with increasing snow depth. This probably reflects an increasing amount of contaminant drag as the snow depth is increased.

b. Snow on Packed Snow – Only a few data are available, which makes it difficult to identify trends. However, the data tend to indicate that the friction coefficient does not change greatly with increasing snow depth.

c. Snow on Pavement – As for the TC SFT'79, the IMAG reading decreases exponentially as the snow depth is increased. As for the "snow on packed snow" case above, this trend may reflect increased bonding between the snow on the surface to the pavement base for deeper depths. This would cause the IMAG to tend to see a snow surface at deeper snow depths.

In conclusion, it is evident that all three devices exhibited different trends depending on the surface being considered. This makes it difficult to identify a cut-off snow depth below which the readings were not affected significantly. To allow the analyses to proceed, two cases were analyzed:

(a) All snow depths
(b) Snow depths of 10 mm or less

These two snow depth cases were analyzed partly because the size of the data set was quite small for snow depths of 10 mm or less. Often, snow depth data were not available for various sets of friction data (although general surface classifications were available), which necessitated these data sets being eliminated from the data subset being analyzed.

The "all snow depths" case includes data for snow depths exceeding 25 mm (1 inch). See Figures 2.3 to 2.9. It is noted that Transport Canada advises that CRFIs not be taken in snow exceeding this depth. It would be useful to further partition the data set to remove the friction values for snow depths exceeding 25 mm (1 inch).

2.3 Friction Measuring Devices Analyzed

Friction coefficients were evaluated in this project for the following devices:

(1) The ERD

(2) The TC SFT'79 – Two cases were analyzed as follows:
   a. All configurations (Table 2.2) – It should be noted that two of the configurations apply to the case where the self-wetting system is on (i.e., configurations 5 and 6 – Table 2.2). Data for these configurations were not included in the results presented here as these configurations would not be used in wintertime conditions. However, the data for these configurations were included in the overall data quantity evaluations that were made (section 2.4).
   b. Configuration 3 (Table 2.2) – This configuration was evaluated separately as it was the most common one used during the JWRFMP.

(3) The IMAG – Two cases were analyzed as follows:
   a. All configurations (Table 2.2)
   b. Configurations 3 and 7 (Table 2.2) – These two configurations were evaluated separately as they were the most common ones used during the JWRFMP.

Table 2.2: List of Configurations

Device	Config'n	Tire Type	Inflation Press (kPa)	Vertical Load (kN)	Slip Ratio (%)	Self-Wetting On?
TC SFT '79	1	ASTM E1551 Ribbed	210	1400	12	no
TC SFT '79	2	ASTM E1551 Ribbed	690	1400	12	no
TC SFT '79	3	ASTM E1551 Smooth	690	1400	12	no
TC SFT '79	4	AERO Smooth Tread	690	1400	12	no
TC SFT '79	5	ASTM E1551 Smooth Tread	690	1400	12	yes
TC SFT '79	6	AERO Smooth Tread	690	1400	12	yes
TC SFT '79	7	ASTM E1551 Ribbed	690	1400	12	no
IMAG	1	PIARC Smooth	150	1800	20	no
IMAG	2	PIARC Smooth	150	1800	5	no
IMAG	3	PIARC Smooth	150	1800	15	no
IMAG	4	PIARC Smooth	150	1800	12	no
IMAG	5	PIARC Smooth	150	1800	50	no
IMAG	6	PIARC Smooth	150	1800	10	no
IMAG	7	PIARC Smooth	165	1800	15	no
IMAG	8	PIARC Smooth	150	1800	15	no
IMAG	9	PIARC Smooth	150	1800	0	no
IMAG	10	PIARC Smooth (note)	165	1800	15	no
IMAG	11	PIARC Smooth	165	1800	30	no
IMAG	12	PIARC Smooth	165	1800	45	no
IMAG	13	PIARC Smooth	165	1800	60	no
IMAG	14	PIARC Smooth	165	1800	75	no
IMAG	15	PIARC Smooth	150	1800	30	no
IMAG	16	PIARC Smooth	150	1800	60	no
IMAG	17	PIARC Smooth	150	1800	90	no
IMAG	18	PIARC Smooth	150	1800	40	no

NOTE: Swapped tires with IRV

2.4 Number of Records

The number of records was checked at the start of the work as this provides an indication of the strength of the conclusions that may be obtained from various analyses. The total number of records for all surfaces and cases was 884, 1029, 938, and 1151 for the ERD, TC SFT'79, IMAG Force, and IMAG Torque, respectively. As expected, the number of records was reduced as the data set was partitioned. See Tables 2.3 to 2.5.

Table 2.3: Data Quantities and Breakdown for the ERD

Configuration Number[1]	Year and Site	Time Interval[2]	Speed[2]	Surface Parameters				Track Section	Number of Data Points
				Base	Surface	Depth[2]	Maintenance Action		
All	All	Blank	Blank	All	All	Blank	None	Whole	884
All	All	Blank	Blank	Ice	All	Blank	None	Whole	328
All	All	Blank	Blank	Ice and Rough Ice	All	Blank	None	Whole	408
All	All	Blank	Blank	Ice	Dry	Blank	None	Whole	196
All	All	Blank	Blank	Ice and Rough Ice	Dry	Blank	None	Whole	239
All	All	Blank	Blank	Packed Snow	All	Blank	None	Whole	223
All	All	Blank	Blank	Packed Snow	Dry	Blank	None	Whole	186
All	All	Blank	Blank	Pavement	All	Blank	None	Whole	183
All	All	Blank	Blank	Pavement	Dry	Blank	None	Whole	13

Notes:

1. The ERD only has one configuration.
2. By leaving this field blank, the program will include all data.

Table 2.4: Data Quantities and Breakdown for the TC SFT'79

Configuration Number	Year and Site	Time Interval[1]	Speed[1]	Surface Parameters				Track Section	Number of Data Points
				Base	Surface	Depth[1]	Maintenance Action		
All[2]	All	Blank	Blank	All	All	Blank	None	Whole	1029
All[2]	All	Blank	Blank	Ice	All	Blank	None	Whole	390
All[2]	All	Blank	Blank	Ice and Rough Ice	All	Blank	None	Whole	465
All[2]	All	Blank	Blank	Ice	Dry	Blank	None	Whole	212
All[2]	All	Blank	Blank	Ice and Rough Ice	Dry	Blank	None	Whole	226
All[2]	All	Blank	Blank	Packed Snow	All	Blank	None	Whole	258
All[2]	All	Blank	Blank	Packed Snow	Dry	Blank	None	Whole	191
All[2]	All	Blank	Blank	Pavement	All	Blank	None	Whole	249
All[2]	All	Blank	Blank	Pavement	Dry	Blank	None	Whole	79
3	All	Blank	Blank	All	All	Blank	None	Whole	760
3	All	Blank	Blank	Ice	All	Blank	None	Whole	314
3	All	Blank	Blank	Ice and Rough Ice	All	Blank	None	Whole	381
3	All	Blank	Blank	Ice	Dry	Blank	None	Whole	174
3	All	Blank	Blank	Ice and Rough Ice	Dry	Blank	None	Whole	188
3	All	Blank	Blank	Packed Snow	All	Blank	None	Whole	214
3	All	Blank	Blank	Packed Snow	Dry	Blank	None	Whole	151
3	All	Blank	Blank	Pavement	All	Blank	None	Whole	131
3	All	Blank	Blank	Pavement	Dry	Blank	None	Whole	24

Notes:

1. By leaving this field blank, the database search wizard will include all data.
2. These data quantities include the data for configurations 5 and 6, which are the ones with the self-wetting system on (Table 2.2). However, the friction data for configurations 5 and 6 were not included in the results presented in section 3 for "all configurations" of the TC SFT'79.

Table 2.5: Data Quantities and Breakdown for the IMAG

Configuration Number	Year and Site	Time Interval[1]	Speed[1]	Surface Parameters				Track Section	Number of Points (IMAG Force/IMAG Torque)
				Base	Surface	Depth[1]	Maintenance Action		
All	All	Blank	Blank	All	All	Blank	None	Whole	938/1151
All	All	Blank	Blank	Ice	All	Blank	None	Whole	372/448
All	All	Blank	Blank	Ice and Rough Ice	All	Blank	None	Whole	460/562
All	All	Blank	Blank	Ice	Dry	Blank	None	Whole	211/247
All	All	Blank	Blank	Ice and Rough Ice	Dry	Blank	None	Whole	254/298
All	All	Blank	Blank	Packed Snow	All	Blank	None	Whole	218/253
All	All	Blank	Blank	Packed Snow	Dry	Blank	None	Whole	158/189
All	All	Blank	Blank	Pavement	All	Blank	None	Whole	215/265
All	All	Blank	Blank	Pavement	Dry	Blank	None	Whole	46/48
3 and 7	All	Blank	Blank	All	All	Blank	None	Whole	881/1082
3 and 7	All	Blank	Blank	Ice	All	Blank	None	Whole	331/407
3 and 7	All	Blank	Blank	Ice and Rough Ice	All	Blank	None	Whole	413/515
3 and 7	All	Blank	Blank	Ice	Dry	Blank	None	Whole	174/210
3 and 7	All	Blank	Blank	Ice and Rough Ice	Dry	Blank	None	Whole	211/255
3 and 7	All	Blank	Blank	Packed Snow	All	Blank	None	Whole	208/235
3 and 7	All	Blank	Blank	Packed Snow	Dry	Blank	None	Whole	148/171
3 and 7	All	Blank	Blank	Pavement	All	Blank	None	Whole	215/261
3 and 7	All	Blank	Blank	Pavement	Dry	Blank	None	Whole	46/48

Notes:

1. By leaving this field blank, the database search wizard will include all data.

3. ANALYSES FOR INDIVIDUAL SURFACES

3.1 Surfaces Quantified in the AIP

The analyses were focused on the surfaces given in the AIP [2], as it is of interest to compare the friction coefficients measured during the JWRFMP with the CRFIs given in the AIP.

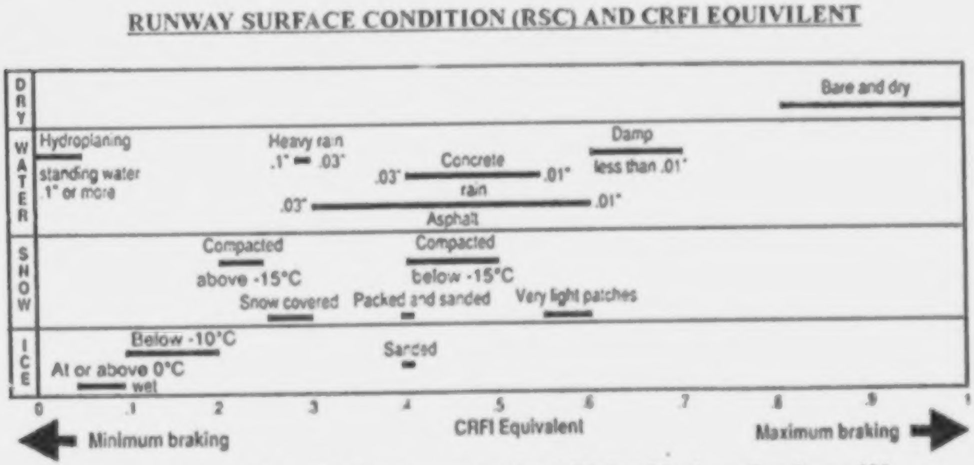


Figure 3.1: CRFIs Given in the AIP for Various Surfaces [2]
(repeated from Figure 2.2)

Summary results are presented in Figures 3.7 to 3.22. It should be noted that, for formatting reasons, all remaining figures associated with section 3 are presented at the end of section 3.

3.2 Bare Ice and Bare Packed Snow

3.2.1 Bare Ice

Figures 3.7 and 3.8 provide summary results for bare ice not including and including rough ice. Summary results are tabulated in Table 3.1. Detailed results are plotted in Appendix A.

The following observations can be made:

(1) Comparison to AIP
  a. Friction coefficients at or above 0°C – The AIP suggests values that tend to be lower than those measured by the devices.
  b. Friction coefficients below -10°C – The values suggested by the AIP are in reasonable agreement with the means measured by the devices.
  c. Overall comparison – The ranges of values suggested by the AIP tend to be smaller than those measured by the devices. In almost all cases, the devices measured values that were both lower than and higher than the lower-bound and upper-bound values suggested by the AIP, respectively.

(2) Effect of Including or Not Including Rough Ice Data – As expected, the inclusion of the rough ice data causes an increase in friction coefficient. However, the increase is relatively

slight, in relation to the overall variation between the maximum and minimum values recorded. Consequently, the conclusions drawn from the analyses will not be affected greatly by whether the rough ice data are included.

This result may be partly due to the fact that the quantity of rough ice data is relatively small compared to that for the smooth ice data. This will cause the friction statistics to be controlled by the smooth ice data.

(3) Effect of Surface Temperature – The friction coefficients measured by each of the devices were not greatly affected by the surface temperature (Appendix A.2).

3.2.2 Bare Packed Snow

Figure 3.9 shows summary results for bare packed snow. Summary results are tabulated in Table 3.2. Detailed results are plotted in Appendix B.

The following observations can be made:

[1] Comparison to AIP
   a. Friction coefficient below -15°C: All of the friction coefficients measured by the devices were substantially less than the values given in the AIP.
   b. Friction coefficient above -15°C: The friction coefficients measured by all of the devices were in general agreement with the range of values in the AIP.
   c. Ranges of friction coefficients: The devices measured a much wider range of friction factors than that given in the AIP.

[2] Effect of Surface Temperature – Typically, there are many more data for surface temperatures above -15°C than below it (Table 3.2), which makes it difficult to infer trends from the summary values listed in Table 3.2. Consequently, the trend plots presented in Appendix B.2 were used to assess the significance of surface temperature. The friction coefficients measured by each of the devices were not greatly affected by the surface temperature (Appendix B.2).

Table 3.1: Summary Results for Bare Ice

Device		Not Including Rough Ice					Including Rough Ice			
ERD		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps
	mean	0.12	0.111506849	0.2	0.119439		0.131818	0.112440476	0.19125	0.12364
	st dev	0.039441	0.046321104	0.132212	0.054448		0.045318	0.04404335	0.111411	0.052914
	maximum	0.21	0.289999992	0.45	0.45		0.24	0.289999992	0.45	0.45
	minimum	0.08	0.050000001	0.08	0.05		0.08	0.050000001	0.1	0.05
	no of obs	10	146	6	196		22	168	8	239
TC SFT'79		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps
(All Configs)	mean	0.183333	0.128797468	0.097273	0.138624		0.178571	0.129127517	0.101667	0.139956
	st dev	0.060625	0.057621183	0.031966	0.067071		0.057652	0.05883937	0.029951	0.067201
	maximum	0.28	0.289999992	0.14	0.42		0.28	0.289999992	0.16	0.42
	minimum	0.05	0.029999999	0.05	0.03		0.05	0.029999999	0.05	0.03
	no of obs	24	158	11	218		28	149	18	226
TC SFT'79		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps
(Config 3)	mean	0.175625	0.1225	No Data	0.132126		0.18	0.12337931	0.09	0.133351
	st dev	0.029205	0.055587768	No Data	0.062432		0.024202	0.055417865	No data	0.062454
	maximum	0.21	0.289999992	0	0.42		0.21	0.289999992	0.09	0.42
	minimum	0.11	0.029999999	0	0.03		0.13	0.029999999	0.09	0.03
	no of obs	16	136	0	174		15	145	1	188
IMAG		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps
Force (All Configs)	mean	0.237667	0.184367816	No Data	0.203415		0.260204	0.196111111	0.21	0.215645
	st dev	0.033803	0.041699398	No Data	0.052758		0.042793	0.045980877	No data	0.056565
	maximum	0.3	0.319999993	0	0.4		0.34	0.319999993	0.21	0.4
	minimum	0.17	0.090000004	0	0.09		0.17	0.109999999	0.21	0.09
	no of obs	30	87	0	205		49	72	1	248
IMAG		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps
Torque (All Configs)	mean	0.155238	0.151214954	0.114	0.146166		0.165652	0.153200001	0.165652	0.150625
	st dev	0.034587	0.038820104	0.014298	0.053049		0.034406	0.04014821	0.128446	0.050515
	maximum	0.22	0.25999999	0.14	0.68		0.23	0.25999999	0.68	0.68
	minimum	0.07	0.07	0.1	0.07		0.07	0.07	0.1	0.07
	no of obs	42	107	10	253		69	100	23	304
IMAG		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps
Force (Configs 3 & 7)	mean	0.235	0.18654321	0.168	0.205238		0.258919	0.191744186	0.14	0.217463
	st dev	0.0373	0.040686621	0.040249	0.045068		0.048177	0.043876615	0.014142	0.050627
	maximum	0.3	0.319999993	0.21	0.37		0.34	0.319999993	0.16	0.37
	minimum	0.17	0.109999999	0.13	0.11		0.17	0.109999999	0.13	0.11
	no of obs	24	81	5	168		37	86	4	205
IMAG		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps
Torque (Configs 3 & 7)	mean	0.157714	0.152475248	0.172941	0.149259		0.165614	0.153867925	0.171875	0.153218
	st dev	0.034733	0.038688653	0.149489	0.054894		0.03713	0.038360961	0.154713	0.051891
	maximum	0.22	0.25999999	0.68	0.68		0.23	0.25999999	0.68	0.68
	minimum	0.07	0.079999998	0.1	0.07		0.07	0.079999998	0.1	0.07
	no of obs	35	101	17	216		57	106	16	261

Table 3.2: Summary Results for Bare Packed Snow

Device		Friction Coefficient by Temperature		
ERD		<=-15°C	>-15°C	All Temperatures
	mean	0.2875	0.184638	0.198817205
	st dev	0.005	0.063501	0.066346338
	maximum	0.29	0.63	0.629999995
	minimum	0.28	0.09	0.090000004
	no of obs	4	138	186
TC SFT'79		<=-15°C	>-15°C	All Temperatures
(All Configs)	mean	0.239375	0.219478	0.226073298
	st dev	0.045088	0.038202	0.042436019
	maximum	0.29	0.35	0.349999994
	minimum	0.16	0.13	0.119999997
	no of obs	16	115	191
TC SFT'79		<=-15°C	>-15°C	All Temperatures
(Config 3)	mean	No Data	0.219333	0.227483444
	st dev	No Data	0.029622	0.042758525
	maximum	0	0.33	0.349999994
	minimum	0	0.14	0.119999997
	no of obs	0	105	151
IMAG		<=-15°C	>-15°C	All Temperatures
Force (All Configs)	mean	0.275714	0.250851	0.263903449
	st dev	0.019101	0.054054	0.053789886
	maximum	0.3	0.37	0.372999996
	minimum	0.25	0.15	0.150000006
	no of obs	14	94	145
IMAG		<=-15°C	>-15°C	All Temperatures
Torque (All Configs)	mean	0.18	0.183511	0.189168318
	st dev	0.021034	0.040704	0.042460064
	maximum	0.22	0.31	0.310000002
	minimum	0.14	0.1	0.100000001
	no of obs	34	131	202
IMAG		<=-15°C	>-15°C	All Temperatures
Force (Configs 3 & 7)	mean	0.28375	0.251429	0.265525927
	st dev	0.020659	0.054845	0.05479471
	maximum	0.3	0.37	0.372999996
	minimum	0.25	0.15	0.150000006
	no of obs	8	91	135
IMAG		<=-15°C	>-15°C	All Temperatures
Torque (Configs 3 & 7)	mean	0.1792	0.183171	0.190391305
	st dev	0.023965	0.041038	0.043324031
	maximum	0.23	0.31	0.310000002
	minimum	0.14	0.1	0.100000001
	no of obs	25	123	184

3.3 Sanded Ice

Figures 3.10 and 3.11 provide summary results for bare ice not including and including rough ice. Summary results are tabulated in Table 3.3. Detailed results are plotted in Appendix C.

The data set for sanded ice is quite small (Table 3.3), which limits the strength of the conclusions that can be drawn. Nevertheless, the following preliminary observations can be made:

(1) Comparison to AIP – The measured friction coefficients span a much wider range of values than that given in the AIP.

(2) Comparison to Un-Sanded Ice – The friction coefficients for sanded ice tend to be higher than those for un-sanded ice.

(3) Effect of Including or Not Including Rough Ice Data – This had no significant effect.

(4) Effect of Surface Temperature – The friction coefficient was not greatly affected by the surface temperature (Appendix C.1).

3.4 Snow on Ice, Pavement and Packed Snow

3.4.1 Snow-Covered Ice

Figures 3.12 and 3.13 provide summary results for snow-covered ice (not including rough ice) for all snow depths, and for snow depths of 10 mm or less, respectively. Figures 3.14 and 3.15 provide summary results for bare ice (including rough ice) for all snow depths, and for snow depths of 10 mm or less, respectively. Summary results are tabulated in Tables 3.4 and 3.5 for bare ice not including and including rough ice, respectively. Detailed results are plotted in Appendix E.

The following observations can be made:

(1) Comparison to AIP – Comparisons are not possible because this case is not covered by the AIP.

(2) Effect of Including or Not Including Rough Ice Data – This did not affect the conclusions significantly due to the large ranges of variation that were measured.

(3) Effect of Including All Snow Depths vs. Limiting the Analyses to Snow Depths of 10 mm or Less – Wider ranges of variation were observed for the full data set. However, the mean friction coefficients were generally similar for each case.

(4) Effect of Surface Temperature – The trends for the whole data set were highly scattered (Appendix D.2), which is partly due to the fact that all snow depths were mixed. However, the plots produced for the data subset with snow depths of 10 mm or less were also scattered (Appendix E.5), which indicates that the friction coefficients were not greatly affected by the surface temperature.

Table 3.3: Summary Results for Sanded Ice

Device		Sanded Ice Not Including Rough Ice					Sanded Ice Including Rough Ice			
ERD		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps
	mean	0.3	0.263333331	0.23	0.241667		0.221111	0.254285714	0.23	0.2325
	st dev	No Data	0.092915735	No Data	0.051316		0.038873	0.067788186	No Data	0.046368
	maximum	0.3	0.340000004	0.23	0.34		0.3	0.340000004	0.23	0.34
	minimum	0.3	0.159999996	0.23	0.16		0.17	0.159999996	0.23	0.16
	no of obs	1	3	1	12		9	7	1	24
TC SFT'79		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps
(All Configs)	mean	No Data	0.636666665	0.11	0.426		No Data	0.636666665	0.11	0.426
	st dev	No Data	0.073936908	0.040825	0.278496		No Data	0.073936908	0.040825	0.278496
	maximum	0	0.699999988	0.17	0.7		0	0.699999988	0.17	0.7
	minimum	0	0.5	0.08	0.08		0	0.5	0.08	0.08
	no of obs	0	6	4	10		0	6	4	10
TC SFT'79		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps
(Config 3)	mean	No Data	0.636666665	No Data	0.636667		No Data	0.636666665	No Data	0.636667
	st dev	No Data	0.073936908	No Data	0.073937		No Data	0.073936908	No Data	0.073937
	maximum	0	0.699999988	0	0.7		0	0.699999988	0	0.7
	minimum	0	0.5	0	0.5		0	0.5	0	0.5
	no of obs	0	6	0	6		0	6	0	6
IMAG		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps
Force (All Configs)	mean	No Data	0.556666662	No Data	0.556667		0.3525	0.556666662	No Data	0.44
	st dev	No Data	0.089591669	No Data	0.089592		0.027646	0.089591669	No Data	0.120384
	maximum	0	0.639999986	0	0.64		0.39	0.639999986	0	0.64
	minimum	0	0.419999987	0	0.42		0.31	0.419999987	0	0.31
	no of obs	0	6	0	6		8	6	0	14
IMAG		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps
Torque (All Configs)	mean	No Data	0.49666667	0.2075	0.381		0.24625	0.292083335	0.2075	0.2725
	st dev	No Data	0.093523619	0.051881	0.167495		0.025036	0.13493893	0.051881	0.115
	maximum	0	0.579999983	0.28	0.58		0.28	0.579999983	0.28	0.58
	minimum	0	0.349999994	0.17	0.17		0.21	0.150000006	0.17	0.15
	no of obs	0	6	4	10		8	24	4	36
IMAG		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps
Force (Configs 3 & 7)	mean	No Data	0.556666662	#DIV/0!	0.556667		0.3525	0.556666662	No Data	0.44
	st dev	No Data	0.089591669	#DIV/0!	0.089592		0.027646	0.089591669	No Data	0.120384
	maximum	0	0.639999986	0	0.64		0.39	0.639999986	0	0.64
	minimum	0	0.419999987	0	0.42		0.31	0.419999987	0	0.31
	no of obs	0	6	0	6		8	6	0	14
IMAG		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps
Torque (Configs 3 & 7)	mean	No Data	0.49666667	0.2075	0.381		0.24625	0.292083335	0.2075	0.2725
	st dev	No Data	0.093523619	0.051881	0.167495		0.025036	0.13493893	0.051881	0.115
	maximum	0	0.579999983	0.28	0.58		0.28	0.579999983	0.28	0.58
	minimum	0	0.349999994	0.17	0.17		0.21	0.150000006	0.17	0.15
	no of obs	0	6	4	10		8	24	4	36

Table 3.4: Summary Results for Snow-Covered Ice – Not Including Rough Ice

Device		Any Snow Depth					Snow Depth < 10 mm			
ERD		<=-10°C	<0°C to >-10	>= 0°C	All Temps		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps
	mean	0.178889	0.17455072	No Data	0.192358		0.24	0.165764706	No Data	0.169889
	st dev	0.05819	0.05930022	No Data	0.073699		0	0.037315249	No Data	0.040128
	maximum	0.24	0.33000001	0	0.39		0.24	0.282999992	0	0.283
	minimum	0.1	0.07	0	0.07		0.24	0.094999999	0	0.095
	no of obs	9	69	0	95		2	34	0	36
TC SFT'79		<=-10°C	<0°C to >-10	>= 0°C	All Temps		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps
(All Configs)	mean	0.177391	0.1614486	No Data	0.166341		0.166364	0.150121952	No Data	0.153558
	st dev	0.093479	0.07975792	No Data	0.081864		0.102788	0.056018834	No Data	0.067659
	maximum	0.33	0.37	0	0.37		0.31	0.370000005	0	0.37
	minimum	0.04	0.04	0	0.04		0.04	0.07	0	0.04
	no of obs	23	107	0	138		11	41	0	52
TC SFT'79		<=-10°C	<0°C to >-10	>= 0°C	All Temps		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps
(Config 3)	mean	0.16	0.15716495	No Data	0.156394		0.16	0.144571429	No Data	0.145789
	st dev	0.01	0.08041853	No Data	0.077774		0.01	0.058828908	No Data	0.056599
	maximum	0.17	0.37	0	0.37		0.17	0.370000005	0	0.37
	minimum	0.15	0.04	0	0.04		0.15	0.07	0	0.07
	no of obs	3	97	0	104		3	35	0	38
IMAG		<=-10°C	<0°C to >-10	>= 0°C	All Temps		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps
Force (All Configs)	mean	0.246333	0.21557895	No Data	0.22296		No Data	0.203333334	No Data	0.203333
	st dev	0.047669	0.07286998	No Data	0.06878		No Data	0.03396831	No Data	0.033968
	maximum	0.33	0.38	0	0.38		0	0.289999992	0	0.29
	minimum	0.18	0.09	0	0.09		0	0.159999996	0	0.16
	no of obs	30	95	0	125		0	27	0	27
IMAG		<=-10°C	<0°C to >-10	>= 0°C	All Temps		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps
Torque (All Configs)	mean	0.1638	0.1653271	No Data	0.165217		0.21375	0.172222222	No Data	0.181714
	st dev	0.053486	0.06402119	No Data	0.060011		0.035832	0.030801264	No Data	0.036095
	maximum	0.26	0.31	0	0.31		0.26	0.239999995	0	0.26
	minimum	0.06	0.03	0	0.03		0.15	0.109999999	0	0.11
	no of obs	50	107	0	161		8	27	0	35
IMAG		<=-10°C	<0°C to >-10	>= 0°C	All Temps		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps
Force (Configs 3 & 7)	mean	0.253333	0.21553192	No Data	0.223967		0.22	0.202692308	No Data	0.203333
	st dev	0.045234	0.07325926	No Data	0.06966		No Data	0.03447407	No Data	0.033968
	maximum	0.33	0.38	0	0.38		0.22	0.289999992	0	0.29
	minimum	0.19	0.09	0	0.09		0.22	0.159999996	0	0.16
	no of obs	27	94	0	121		1	26	0	27
IMAG		<=-10°C	<0°C to >-10	>= 0°C	All Temps		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps
Torque (Configs 3 & 7)	mean	0.167234	0.16584906	No Data	0.166624		0.202222	0.174615385	No Data	0.181714
	st dev	0.053312	0.06409618	No Data	0.060102		0.048161	0.028737538	No Data	0.036095
	maximum	0.26	0.31	0	0.31		0.26	0.239999995	0	0.26
	minimum	0.06	0.03	0	0.03		0.11	0.140000001	0	0.11
	no of obs	47	106	0	157		9	26	0	35

Table 3.5: Summary Results for Snow-Covered Ice – Including Rough Ice

Device		Any Snow Depth					Snow Depth < 10 mm			
ERD		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps		<=-10°C	<0°C to >-10°	>= 0°C	All Temps
	mean	0.149444	0.180695652	No Data	0.188326		0.253333	0.16910204	No Data	0.173887
	st dev	0.065212	0.058113898	No Data	0.070961		0.023094	0.038762226	No Data	0.042349
	maximum	0.28	0.330000013	0	0.39		0.28	0.282999992	0	0.283
	minimum	0.09	0.07	0	0.07		0.24	0.094999999	0	0.095
	no of obs	18	92	0	129		3	49	0	53
TC SFT'79		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps		<=-10°C	<0°C to >-10°	>= 0°C	All Temps
(All Configs)	mean	0.191111	0.166007463	0.1025	0.168636		0.194	0.164402986	No Data	0.169817
	st dev	0.092584	0.076595265	0.023629	0.076791		0.099484	0.059838941	No Data	0.068998
	maximum	0.33	0.370000005	0.12	0.37		0.31	0.370000005	0	0.37
	minimum	0.04	0.039999999	0.07	0.04		0.04	0.07	0	0.04
	no of obs	27	134	4	187		15	67	0	82
TC SFT'79		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps		<=-10°C	<0°C to >-10°	>= 0°C	All Temps
(Config 3)	mean	0.170714	0.160826772	No Data	0.161069		0.1775	0.1615	No Data	0.1625
	st dev	0.020178	0.076492463	No Data	0.072005		0.03594	0.062309371	No Data	0.060932
	maximum	0.23	0.370000005	0	0.37		0.23	0.370000005	0	0.37
	minimum	0.15	0.039999999	0	0.04		0.15	0.07	0	0.07
	no of obs	14	127	0	145		4	60	0	64
IMAG		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps		<=-10°C	<0°C to >-10°	>= 0°C	All Temps
Force (All Configs)	mean	0.250526	0.211491229	No Data	0.222911		No Data	0.198260869	No Data	0.205962
	st dev	0.043243	0.06952726	No Data	0.065368		No Data	0.039231751	No Data	0.042898
	maximum	0.33	0.379999995	0	0.38		0	0.289999992	0	0.29
	minimum	0.18	0.090000004	0	0.09		0	0.140000001	0	0.14
	no of obs	38	114	0	158		0	46	0	52
IMAG		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps		<=-10°C	<0°C to >-10°	>= 0°C	All Temps
Torque (All Configs)	mean	0.159848	0.16	No Data	0.160991		0.205	0.153913044	No Data	0.16625
	st dev	0.055206	0.059603628	No Data	0.056923		0.03451	0.038208682	No Data	0.041077
	maximum	0.26	0.310000002	0	0.31		0.26	0.239999995	0	0.26
	minimum	0.02	0.029999999	0	0.02		0.15	0.100000001	0	0.1
	no of obs	66	136	0	212		12	46	0	64
IMAG		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps		<=-10°C	<0°C to >-10°	>= 0°C	All Temps
Force (Configs 3 & 7)	mean	0.256286	0.21141593	No Data	0.223701		0.22	0.197777778	No Data	0.205962
	st dev	0.040226	0.06983229	No Data	0.066006		No Data	0.039536453	No Data	0.042898
	maximum	0.33	0.379999995	0	0.38		0.22	0.289999992	0	0.29
	minimum	0.19	0.090000004	0	0.09		0.22	0.140000001	0	0.14
	no of obs	35	113	0	154		1	45	0	52
IMAG		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps		<=-10°C	<0°C to >-10°	>= 0°C	All Temps
Torque (Configs 3 & 7)	mean	0.162222	0.16037037	No Data	0.161971		0.197692	0.154888889	No Data	0.16625
	st dev	0.055371	0.059668329	No Data	0.057015		0.04226	0.038056311	No Data	0.041077
	maximum	0.26	0.310000002	0	0.31		0.26	0.239999995	0	0.26
	minimum	0.02	0.029999999	0	0.02		0.11	0.100000001	0	0.1
	no of obs	63	135	0	208		13	45	0	64

3.4.2 Snow-Covered Pavement

Figures 3.16 and 3.17 provide summary results for snow-covered pavement for all snow depths, and for snow depths of 10 mm or less, respectively. Summary results are tabulated in Table 3.6. Detailed results are plotted in Appendix D.

The following observations can be made:

(1) Comparison to AIP – Comparisons are not possible, as the AIP does not provide guideline CRFI values for this case.

(2) Ranges of Values – The measured values span a wide range for each device and each snow depth case analyzed.

(3) Effect of Limiting the Analyses to Snow Depths of 10 mm or Less – The friction coefficients were lower for the "10 mm or Less" case, particularly with respect to mean values.

(4) Effect of Surface Temperature – Typically, there are many more data for surface temperatures in the range of 0°C to -10°C than for the other temperature ranges (Table 3.6), which makes it difficult to infer trends from the summary values listed in Table 3.6. Consequently, the trend plots presented in Appendices D.2 and D.5 were used to assess the significance of surface temperature. The plots are highly scattered for both snow depth cases (Appendices D.2 and D.5), which indicates that the friction coefficients are not strongly related to the surface temperature.

3.4.3 Snow-Covered Packed Snow

Figures 3.18 and 3.19 provide summary results for snow-covered packed snow for all snow depths, and for snow depths of 10 mm or less, respectively. Summary results are tabulated in Table 3.7. Detailed results are plotted in Appendix F.

The following observations can be made:

(1) Comparison to AIP – The measured friction coefficients are in reasonable agreement with the values in the AIP. Furthermore, the ranges of variation are generally similar.

(2) Effect of Including All Snow Depths vs. Limiting the Analyses to Snow Depths of 10 mm or Less – The friction coefficients are lower for the "10 mm or Less" case. As well, the ranges of variation are much smaller than the "10 mm or Less" case.

(3) Effect of Surface Temperature – The plots are quite scattered (Appendices F.2 and F.5), which indicates that the friction coefficients are not greatly affected by the surface temperature.

Table 3.6: Summary Results for Snow on Pavement

Device		All Snow Depths					Snow Depths of 10 mm or Less			
ERD		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps
	mean	0.298571	0.279827588	0.515	0.306116		0.29	0.294999999	0.515	0.33
	st dev	0.040591	0.110286571	0.047958	0.10447		#DIV/0!	0.111897504	0.047958	0.130352
	maximum	0.36	0.660000026	0.58	0.66		0.29	0.649999976	0.58	0.65
	minimum	0.23	0.140000001	0.47	0.14		0.29	0.140000001	0.47	0.14
	no of obs	7	58	4	121		1	20	4	25
TC SFT'79		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps
(All Configs)	mean	0.195833	0.188472223	0.2225	0.171626		0.29	0.263636363	0.2225	0.261667
	st dev	0.077748	0.15936193	0.078475	0.131631		0.008165	0.232185178	0.078475	0.200019
	maximum	0.3	0.730000019	0.3	0.73		0.3	0.730000019	0.3	0.73
	minimum	0.07	0.01	0.15	0.01		0.28	0.07	0.15	0.07
	no of obs	12	72	4	123		4	22	4	30
TC SFT'79		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps
(Config 3)	mean	No Data	0.200000001	0.2225	0.17974		No Data	0.210555555	0.2225	0.212727
	st dev	No Data	0.158972767	0.078475	0.133515		No Data	0.221265671	0.078475	0.201333
	maximum	0	0.730000019	0.3	0.73		0	0.730000019	0.3	0.73
	minimum	0	0.01	0.15	0.01		0	0.07	0.15	0.07
	no of obs	0	48	4	77		0	18	4	22
IMAG		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps
Force (All Configs)	mean	No Data	0.282753624	0.265	0.277944		No Data	0.303448276	0.254286	0.293889
	st dev	No Data	0.145419109	0.057975	0.120891		No Data	0.207231336	0.067788	0.188502
	maximum	0	0.870000005	0.34	0.87		0	0.870000005	0.34	0.87
	minimum	0	0.140000001	0.16	0.14		0	0.140000001	0.16	0.14
	no of obs	0	69	10	107		0	29	7	36
IMAG		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps
Torque (All Configs)	mean	0.161667	0.174731183	0.17	0.163333		0.188333	0.197575756	0.19	0.195217
	st dev	0.048399	0.142756949	0.06532	0.117002		0.031885	0.208851475	0.068557	0.178248
	maximum	0.23	0.829999983	0.3	0.83		0.23	0.829999983	0.3	0.83
	minimum	0.08	0.02	0.1	0.02		0.14	0.02	0.1	0.02
	no of obs	12	93	10	159		6	33	7	46
IMAG		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps
Force (Configs 3 & 7)	mean	No Data	0.282941177	0.265	0.277944		No Data	0.303448276	0.254286	0.293889
	st dev	No Data	0.146491899	0.057975	0.120891		No Data	0.207231336	0.067788	0.188502
	maximum	0	0.870000005	0.34	0.87		0	0.870000005	0.34	0.87
	minimum	0	0.140000001	0.16	0.14		0	0.140000001	0.16	0.14
	no of obs	0	68	10	107		0	29	7	36
IMAG		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps		<=-10°C	<0°C to >-10°C	>= 0°C	All Temps
Torque (Configs 3 & 7)	mean	0.161667	0.174761905	0.17	0.166516		0.188333	0.219310344	0.19	0.21
	st dev	0.048399	0.143941723	0.06532	0.116767		0.031885	0.213974814	0.068557	0.179661
	maximum	0.23	0.829999983	0.3	0.83		0.23	0.829999983	0.3	0.83
	minimum	0.08	0.050000001	0.1	0.02		0.14	0.050000001	0.1	0.05
	no of obs	12	84	10	155		6	29	7	42

Table 3.7: Summary Results for Snow-Covered Packed Snow

Device		All Snow Depths				Snow Depths of 10 mm or Less		
ERD		<=-15°C	> -15°C	All Temps		<=-15°C	> -15°C	All Temps
	mean	No Data	0.201818	0.211481		No Data	0.22125	0.22125
	st dev	No Data	0.047972	0.047935		No Data	0.04051	0.04051
	maximum	0	0.32	0.32		0	0.27	0.27
	minimum	0	0.12	0.12		0	0.17	0.17
	no of obs	0	22	27		0	8	8
TC SFT'79		<=-15°C	> -15°C	All Temps		<=-15°C	> -15°C	All Temps
(All Configs)	mean	No Data	0.204815	0.205625		No Data	0.246	0.246
	st dev	No Data	0.057135	0.052667		No Data	0.011738	0.011738
	maximum	0	0.33	0.33		0	0.26	0.26
	minimum	0	0.09	0.09		0	0.23	0.23
	no of obs	0	27	32		0	10	10
TC SFT'79		<=-15°C	> -15°C	All Temps		<=-15°C	> -15°C	All Temps
(Config 3)	mean	No Data	0.221304	0.219286		No Data	0.246	0.246
	st dev	No Data	0.043621	0.040086		No Data	0.011738	0.011738
	maximum	0	0.33	0.33		0	0.26	0.26
	minimum	0	0.16	0.16		0	0.23	0.23
	no of obs	0	23	28		0	10	10
IMAG		<=-15°C	> -15°C	All Temps		<=-15°C	> -15°C	All Temps
Force (All Configs)	mean	No Data	0.233684	0.241667		No Data	0.243333	0.243333
	st dev	No Data	0.059462	0.05522		No Data	0.01633	0.01633
	maximum	0	0.41	0.41		0	0.26	0.26
	minimum	0	0.16	0.16		0	0.22	0.22
	no of obs	0	19	24		0	6	6
IMAG		<=-15°C	> -15°C	All Temps		<=-15°C	> -15°C	All Temps
Torque (All Configs)	mean	No Data	0.154783	0.161429		No Data	0.178333	0.178333
	st dev	No Data	0.045614	0.043861		No Data	0.004082	0.004082
	maximum	0	0.33	0.33		0	0.18	0.18
	minimum	0	0.1	0.1		0	0.17	0.17
	no of obs	0	23	28		0	6	6
IMAG		<=-15°C	> -15°C	All Temps		<=-15°C	> -15°C	All Temps
Force (Configs 3 & 7)	mean	No Data	0.233684	0.241667		No Data	0.243333	0.243333
	st dev	No Data	0.059462	0.05522		No Data	0.01633	0.01633
	maximum	0	0.41	0.41		0	0.26	0.26
	minimum	0	0.16	0.16		0	0.22	0.22
	no of obs	0	19	24		0	6	6
IMAG		<=-15°C	> -15°C	All Temps		<=-15°C	> -15°C	All Temps
Torque (Configs 3 & 7)	mean	No Data	0.154783	0.161429		No Data	0.178333	0.178333
	st dev	No Data	0.045614	0.043861		No Data	0.004082	0.004082
	maximum	0	0.33	0.33		0	0.18	0.18
	minimum	0	0.1	0.1		0	0.17	0.17
	no of obs	0	23	28		0	6	6

3.5 Slush on Any Base Surface

Figure 3.20 provides summary results for slush on any base surface. Summary results are tabulated in Table 3.8. Detailed results are plotted in Appendix G.

Only a few data points are available, which limits the strength of the conclusions that can be drawn (Table 3.8). Furthermore, only very limited slush depth data are available. For the ERD results, slush depth data are available for only 10 of the 34 friction observations. The measured depths are highly variable, ranging from 8 mm to 50 mm. No slush depth data are available for correlation with the TC SFT'79 and IMAG friction data. This further limits the strength of the conclusions that can be drawn. Nevertheless, some preliminary observations can be made as follows:

(1) Ranges of Variation – The measured friction coefficients span a wide range for each device.
(2) Friction Coefficient Magnitudes – These tend to be higher than those for bare ice or bare packed snow.

3.6 Wet Pavement

Figure 3.21 provides summary results for wet pavement. Summary results are tabulated in Table 3.8. Detailed results are plotted in Appendix H. Only a few data points are available, which limits the strength of the conclusions that can be drawn (Table 3.8). Nevertheless, some preliminary observations can be made as follows:

(1) Comparison to AIP – The measured friction coefficients are generally higher than those in the AIP.
(2) Ranges of Variation – The measured friction coefficients span a wide range for each device.

3.7 Dry Pavement

Figure 3.22 provides summary results for dry pavement. Summary results are tabulated in Table 3.8. Detailed results are plotted in Appendix I. Although only a few data points are available (Table 3.8), some preliminary observations can be made as follows:

(1) Comparison to AIP – The measured friction factors are lower than those in the AIP.
(2) Ranges of Variation – The ranges for each device are similar to those in the AIP.
(3) Wet vs. Dry Pavement – The ERD indicated higher friction on average for wet pavement than for dry pavement (Table 3.8). This may reflect variations in texture among the different sites included in the observations used to establish the average.

Table 3.8: Summary Results for Slush, Wet Pavement and Dry Pavement

Device		Slush on Any Base Surface	Wet Pavement	Dry Pavement
ERD		All Temperatures	All Temperatures	All Temperatures
	mean	0.305882352	0.709130445	0.696923082
	st dev	0.121508638	0.079252929	0.065368777
	maximum	0.629999995	0.829999983	0.810000002
	minimum	0.090000004	0.540000021	0.589999974
	no of obs	34	23	13
TC SFT'79		All Temperatures		All Temperatures
(All Configs)	mean	0.229999997		0.875344826
	st dev	0.152970581		0.048130506
	maximum	0.569999993		1
	minimum	0.079999998		0.779999971
	no of obs	17		58
TC SFT'79		All Temperatures	All Temperatures	All Temperatures
(Config 3)	mean	0.236153843	0.807619049	0.905833331
	st dev	0.174381687	0.059405784	0.03752294
	maximum	0.569999993	0.920000017	1
	minimum	0.079999998	0.680000007	0.850000024
	no of obs	13	21	24
IMAG		All Temperatures		All Temperatures
Force (All Configs)	mean	0.27625		0.735652179
	st dev	0.149883289		0.063092598
	maximum	0.680000007		0.910000026
	minimum	0.109999999		0.589999974
	no of obs	16		46
IMAG		All Temperatures		All Temperatures
Torque (All Configs)	mean	0.218		0.69333333
	st dev	0.127510577		0.056052157
	maximum	0.629999995		0.860000014
	minimum	0.109999999		0.589999974
	no of obs	20		48
IMAG		All Temperatures	All Temperatures	All Temperatures
Force (Configs 3 & 7)	mean	0.27625	0.690638295	0.735652179
	st dev	0.149883289	0.049537173	0.063092598
	maximum	0.680000007	0.839999974	0.910000026
	minimum	0.109999999	0.589999974	0.589999974
	no of obs	16	47	46
IMAG		All Temperatures	All Temperatures	All Temperatures
Torque (Configs 3 & 7)	mean	0.218	0.624705884	0.69333333
	st dev	0.127510577	0.172108722	0.056052157
	maximum	0.629999995	0.819999993	0.860000014
	minimum	0.109999999	0.050000001	0.589999974
	no of obs	20	51	48

3.8 Direct Comparisons with the CRFI Values in the AIP

3.8.1 Presentation of Results

Figures 3.2 to 3.5 show summary results for the ERD, the TC SFT'79 in configuration 3, the IMAG Force in configurations 3 or 7, and the IMAG Torque in configurations 3 or 7, respectively. For reference, the CRFI values currently in the AIP are re-plotted in Figure 3.22.

3.8.2 Ice Surfaces

The following comments can be made:

(a) "Cold" (below -10°C) vs. "Warm" (at or above 0°C) Ice – The AIP values indicate a sharp distinction between cold and warm ice, with higher CRFIs for warm ice.

The devices do not show such a distinction. The ERD, the TC SFT'79 (configuration 3) and the IMAG Torque (configurations 3 or 7) all show higher CRFIs for warm ice than cold ice. The IMAG Force (configurations 3 or 7) indicates similar CRFIs for warm and cold ice.

(b) Sanded Ice – The AIP indicates that sanded ice can be expected to have a CRFI that is much larger than bare ice. Furthermore, it indicates that the CRFI for sanded ice will lie in a narrow range.

The devices gave CRFI values that spanned a wide range. The range of CRFIs measured for sanded ice was similar to that for bare ice.

3.8.3 Packed Snow

The following comments can be made:

(a) Effect of Temperature – The CRFIs in the AIP are much higher for "cold" packed snow (i.e., below -15°C).

The ERD and the IMAG both measured CRFIs that are not greatly different over the full range of temperatures. Data are not available for the TC SFT'79 at below -15°C, and thus, comparisons cannot be made for it.

(b) Packed Snow vs. Bare Ice – The CRFIs in the AIP are significantly higher for packed snow than for bare ice.

The measured values do not exhibit a clear difference between bare ice and bare packed snow, although they are slightly higher for packed snow.

(c) Snow on a Packed Snow Base – The AIP indicates that the CRFI for snow-covered packed snow will lie between the values for bare "warm" and "cold" packed snow.

The measured values for snow-covered packed snow are similar to those for bare packed snow.

3.8.4 Wet Pavement

The measured CRFIs are generally similar to those given in the AIP for damp pavement.

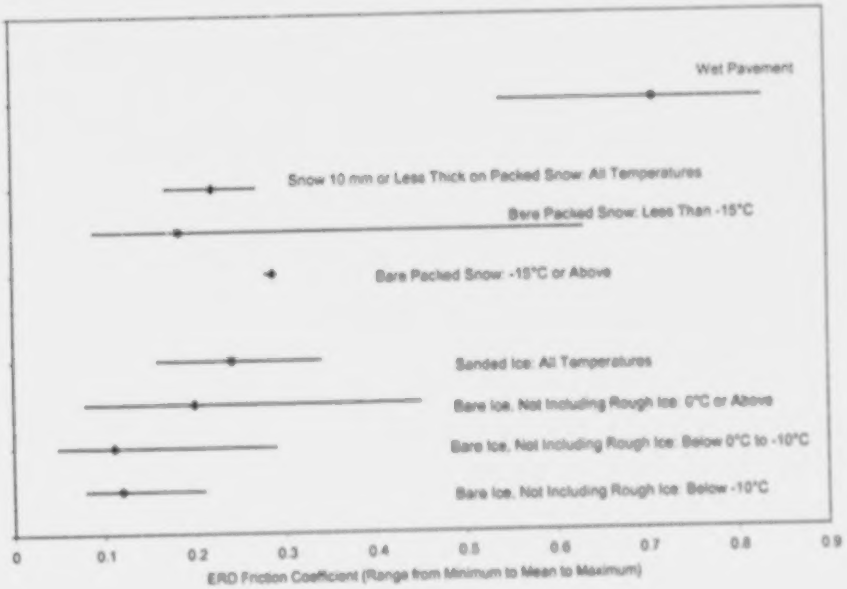


Figure 3.2: Summary Results for the ERD

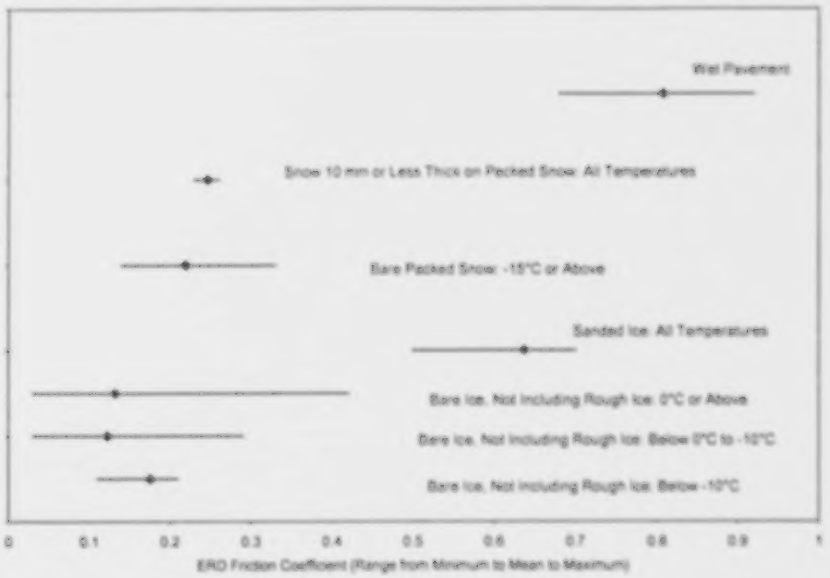


Figure 3.3: Summary Results for the TC SFT'79 in Configuration 3

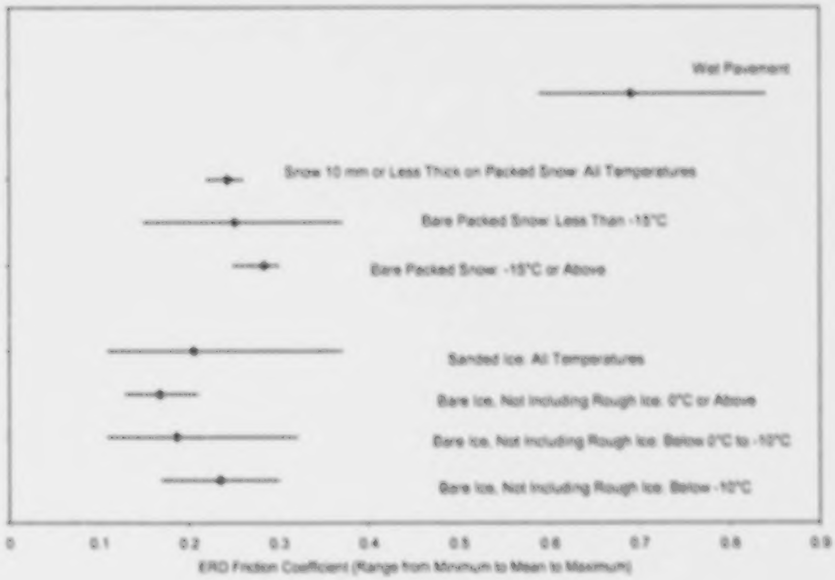


Figure 3.4: Summary Results for the IMAG Force in Configuration 3 or 7

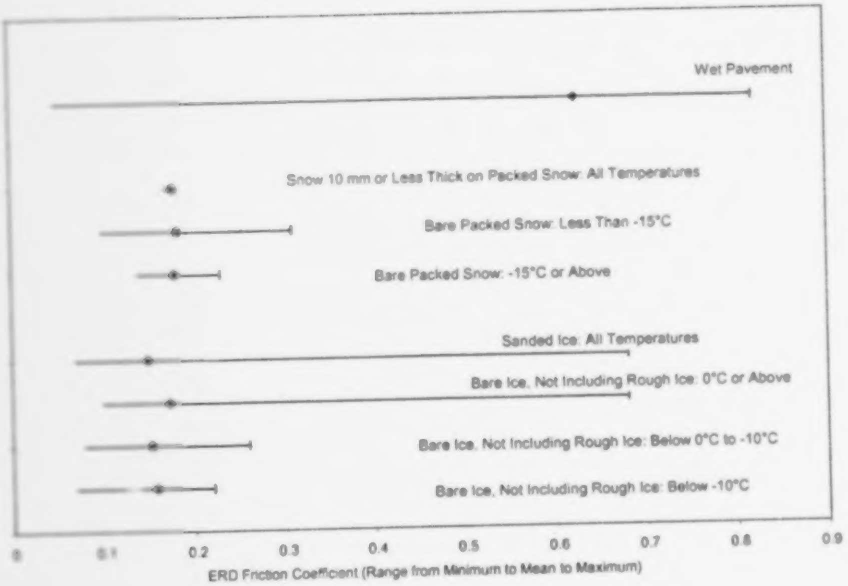


Figure 3.5: Summary Results for the IMAG Torque in Configuration 3 or 7

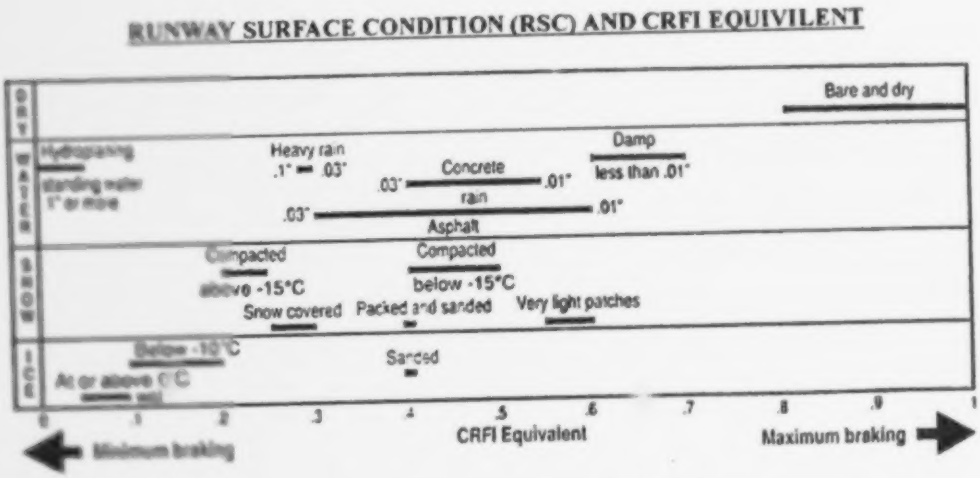


Figure 3.6: CRFIs Given in the AIP for Various Surfaces [2]
(repeated from Figure 2.2)

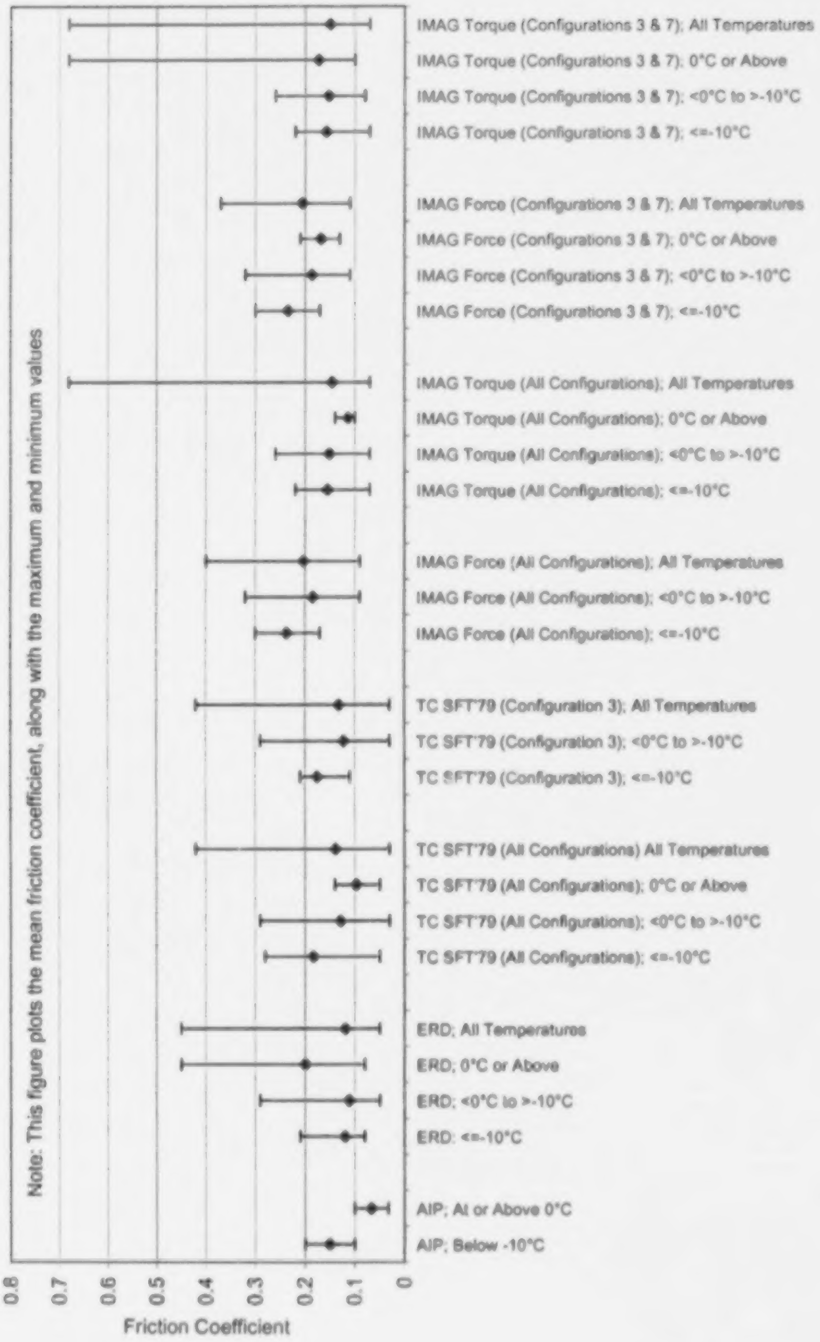


Figure 3.7: Friction Coefficients on Bare Ice: Summary Results

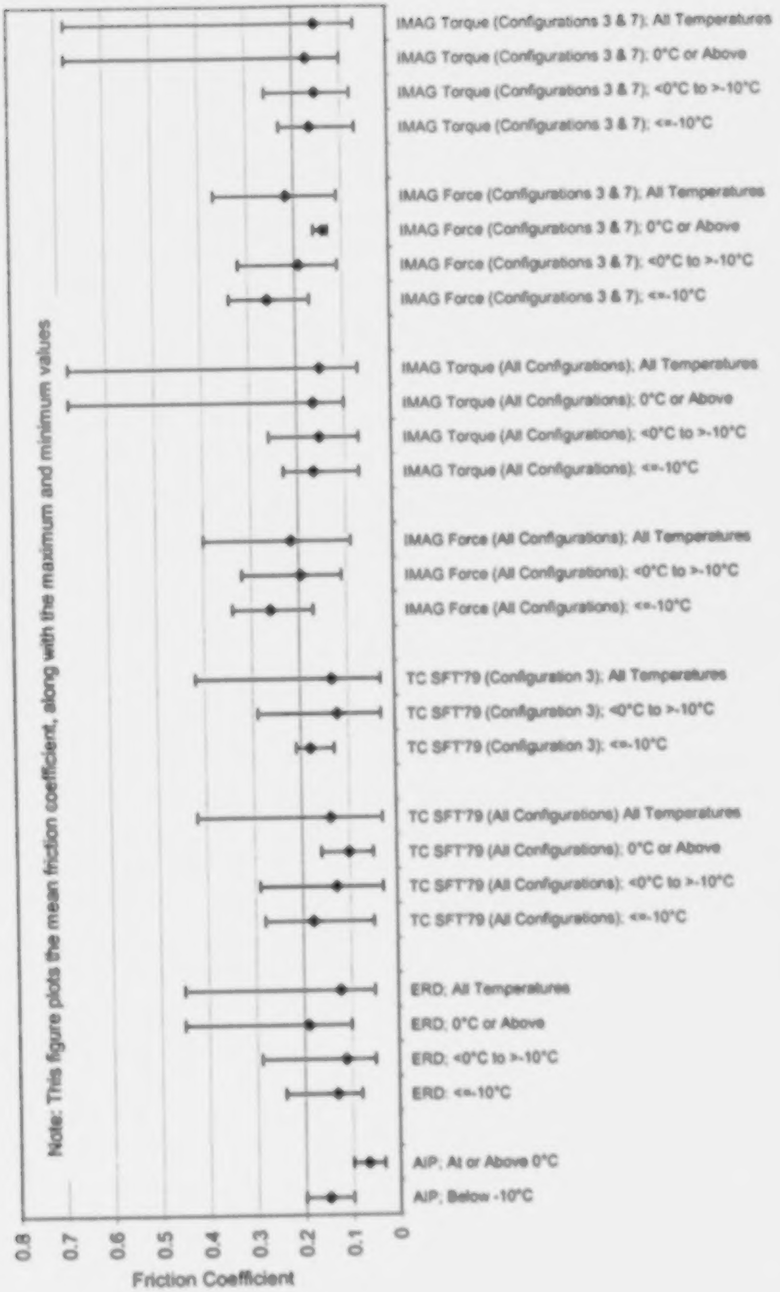


Figure 3.8: Friction Coefficients on Bare Ice Including Rough Ice: Summary Results

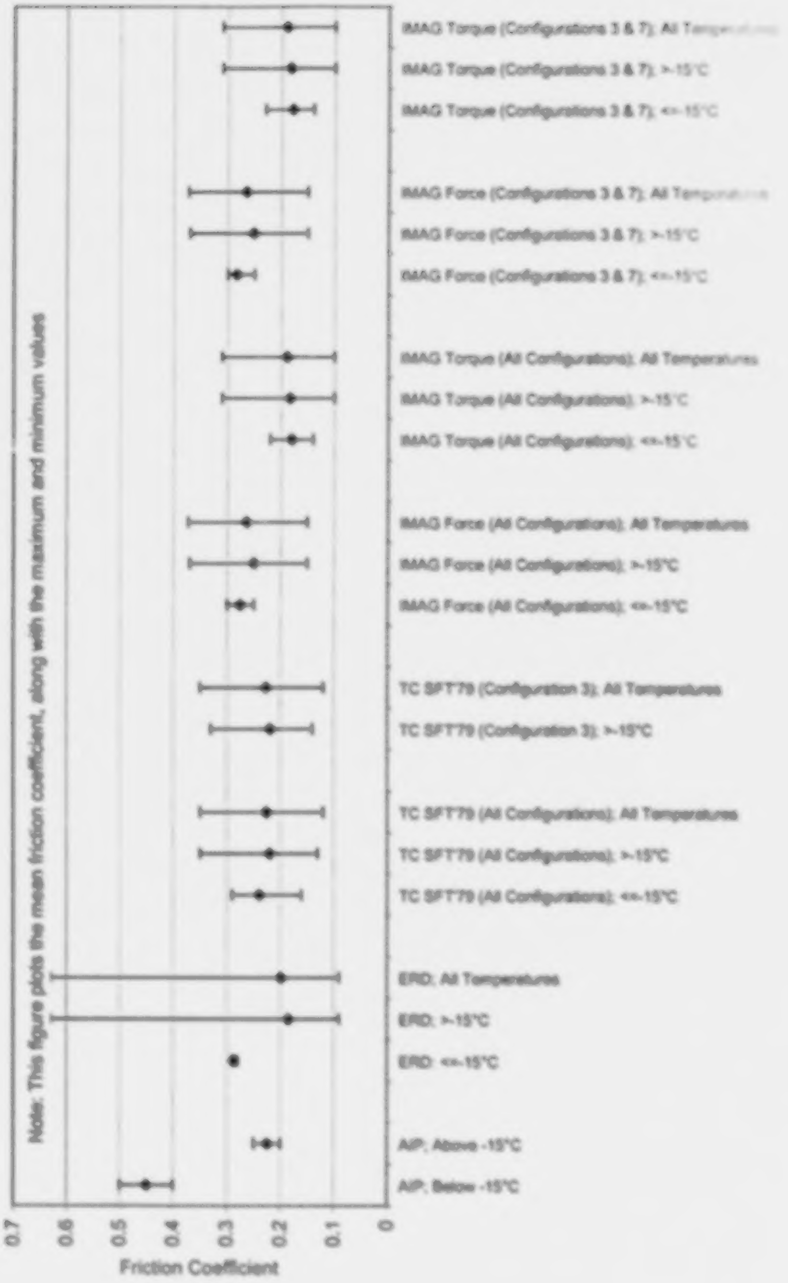


Figure 3.9: Friction Coefficients on Bare Packed Snow: Summary Results

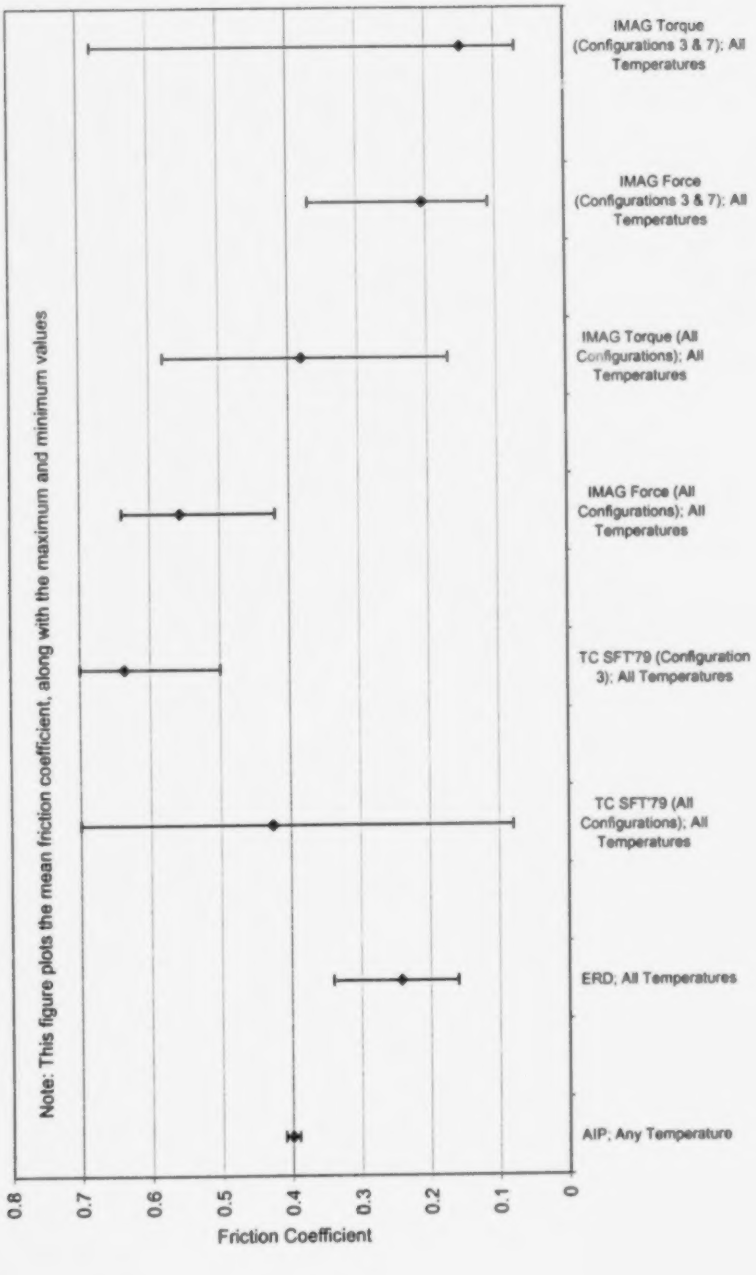


Figure 3.10: Friction Coefficients on Sanded Ice: Summary Results

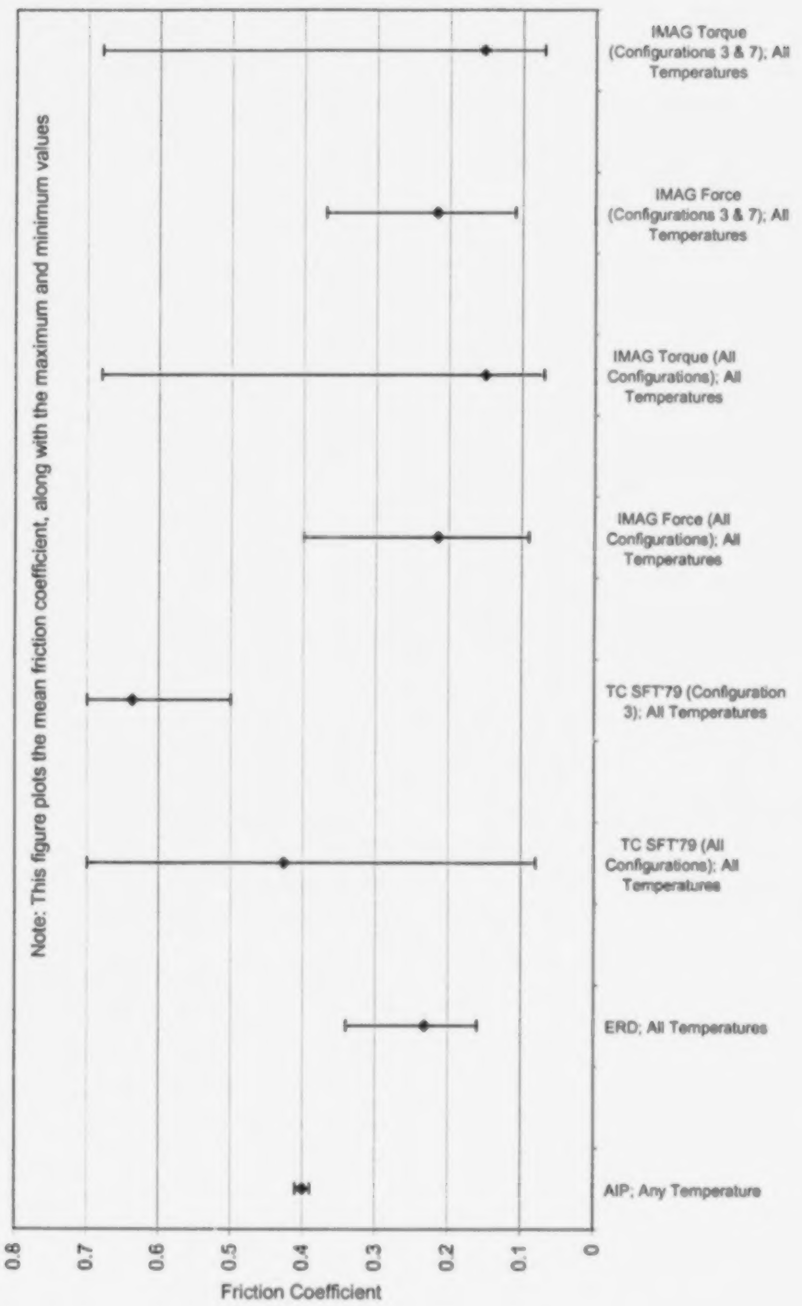


Figure 3.11: Friction Coefficients on Sanded Ice Including Rough Ice: Summary Results

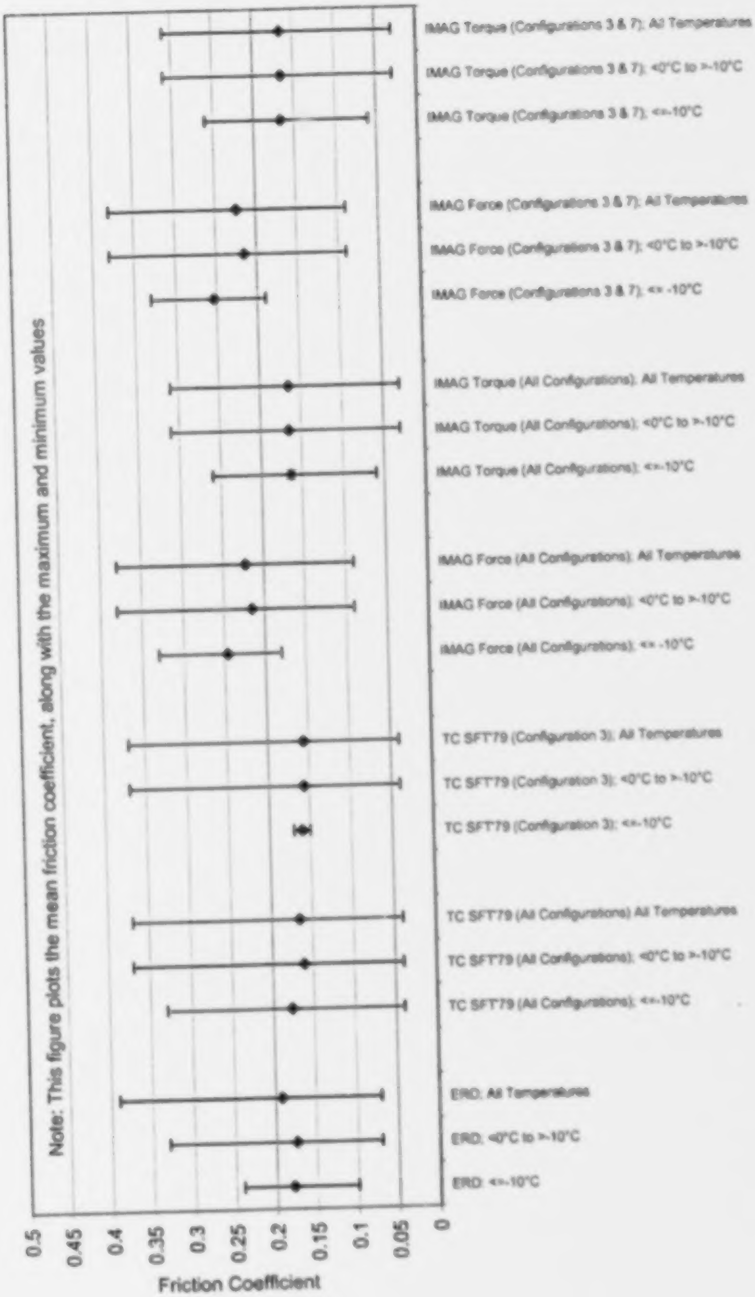


Figure 3.12: Friction Coefficients on Snow Covered Ice (All Depths of Snow Cover): Summary Results

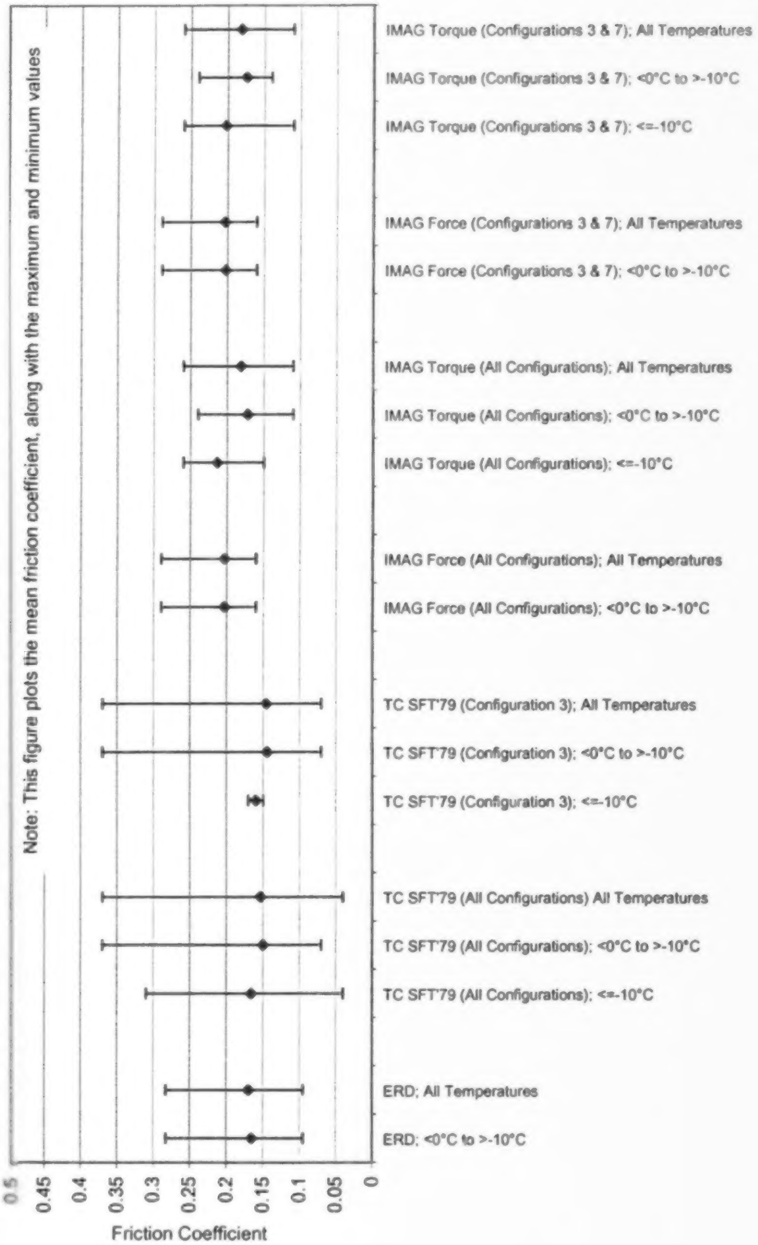


Figure 3.13: Friction Coefficient on Snow Covered Ice (Snow Cover 10 mm or Less Thick): Summary Results

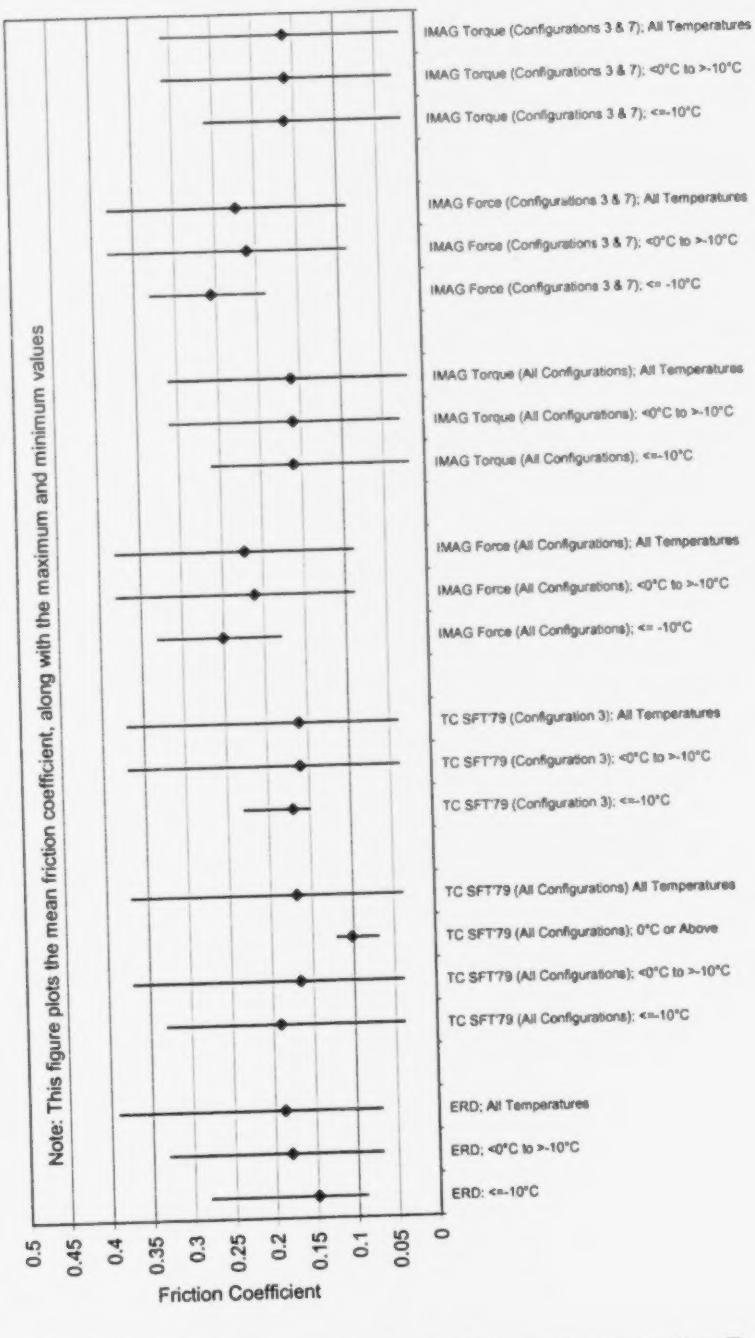


Figure 3.14: Friction Coefficients on Snow Covered Ice Including Rough Ice (All Depths of Snow Cover): Summary Results

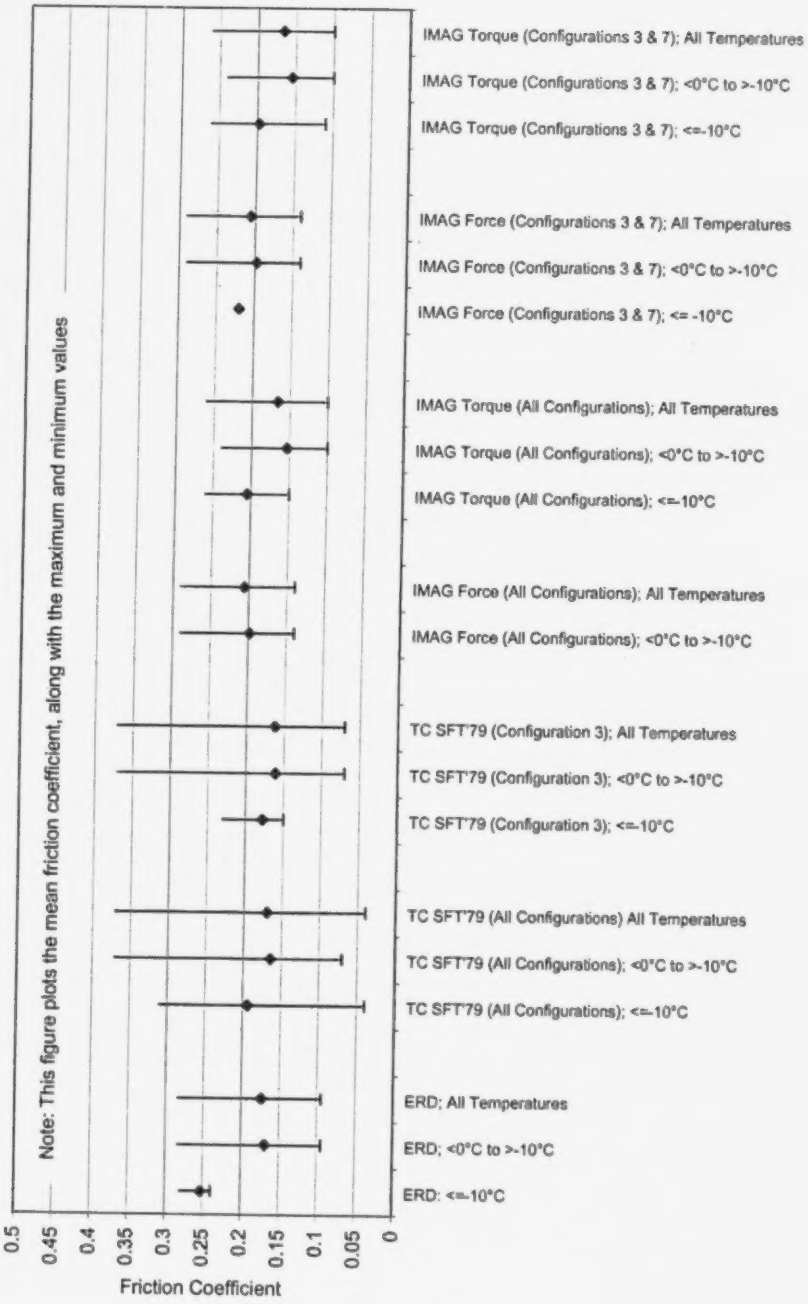
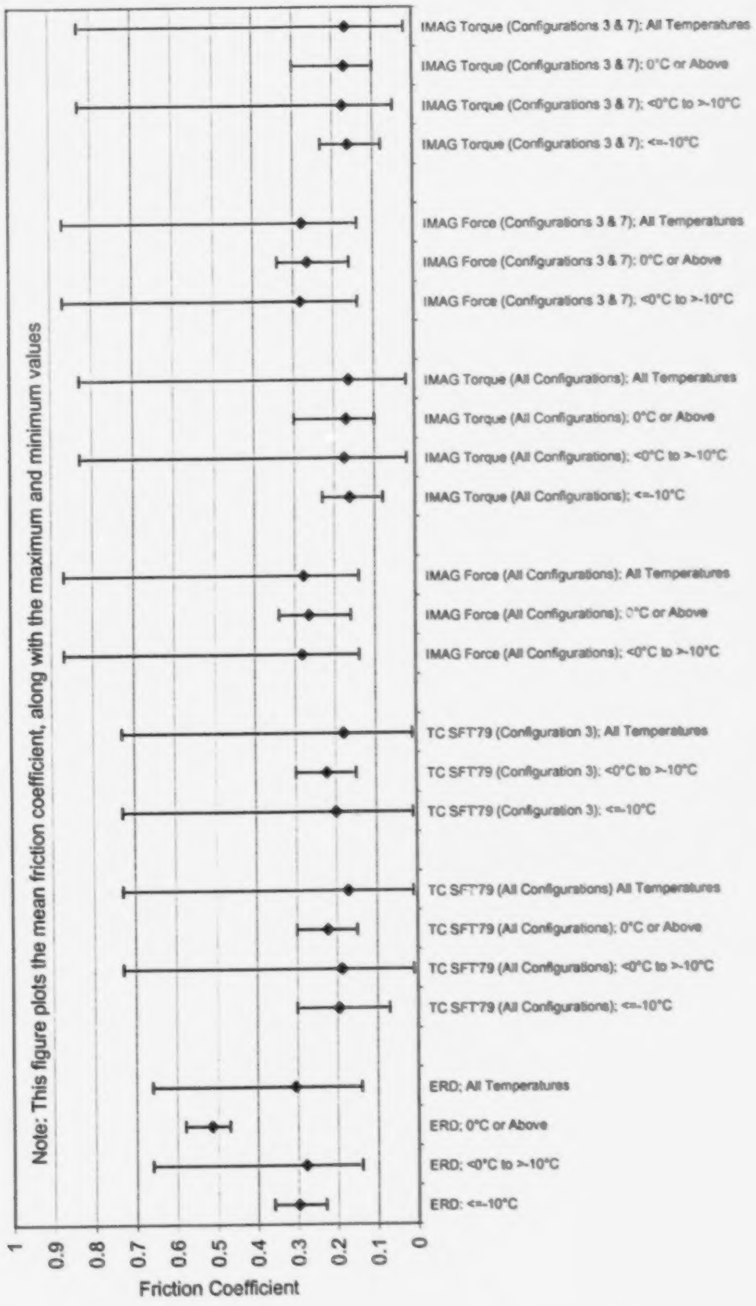


Figure 3.15: Friction Coefficients on Snow Covered Ice Including Rough Ice (Snow Cover 10 mm or Less Thick): Summary Results



Note: This figure plots the mean friction coefficient, along with the maximum and minimum values

Figure 3.16: Friction Coefficients on Snow Covered Pavement (All Depths of Snow Cover): Summary Results

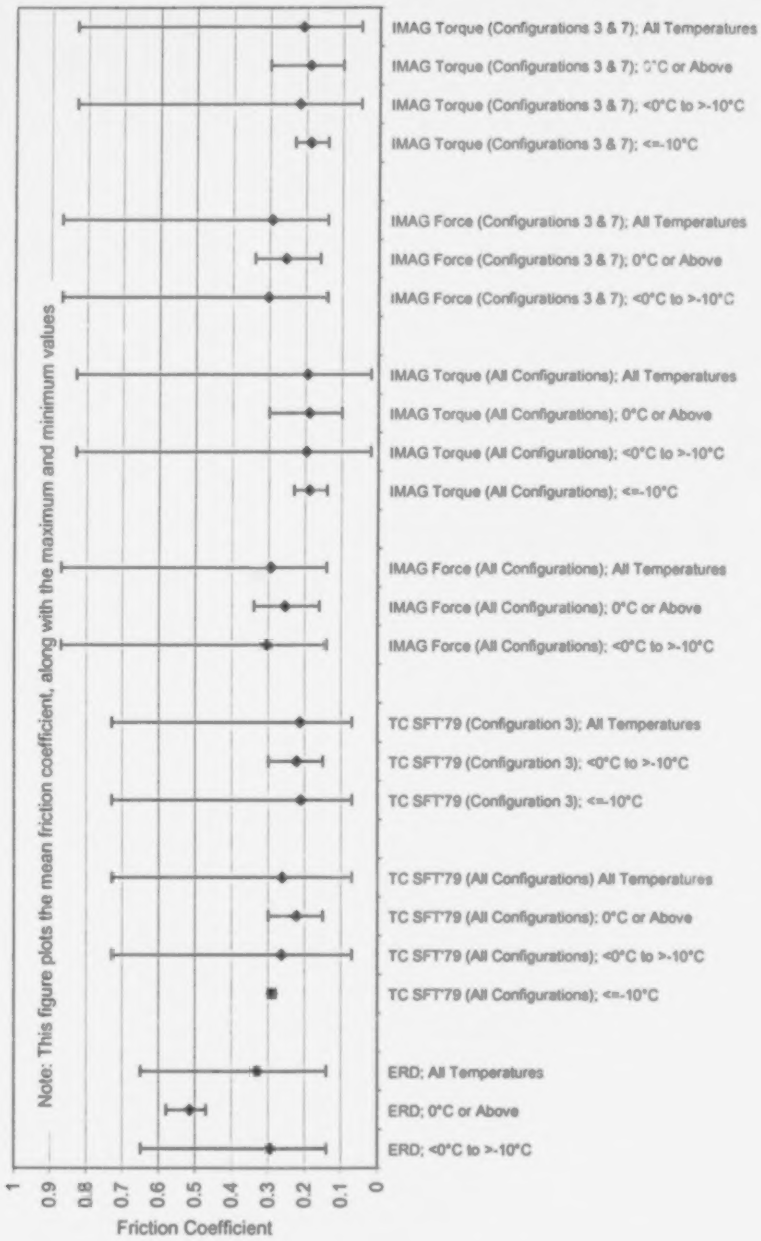


Figure 3.17: Friction Coefficients on Snow Covered Pavement (Snow Cover 10 mm or Less Thick): Summary Results

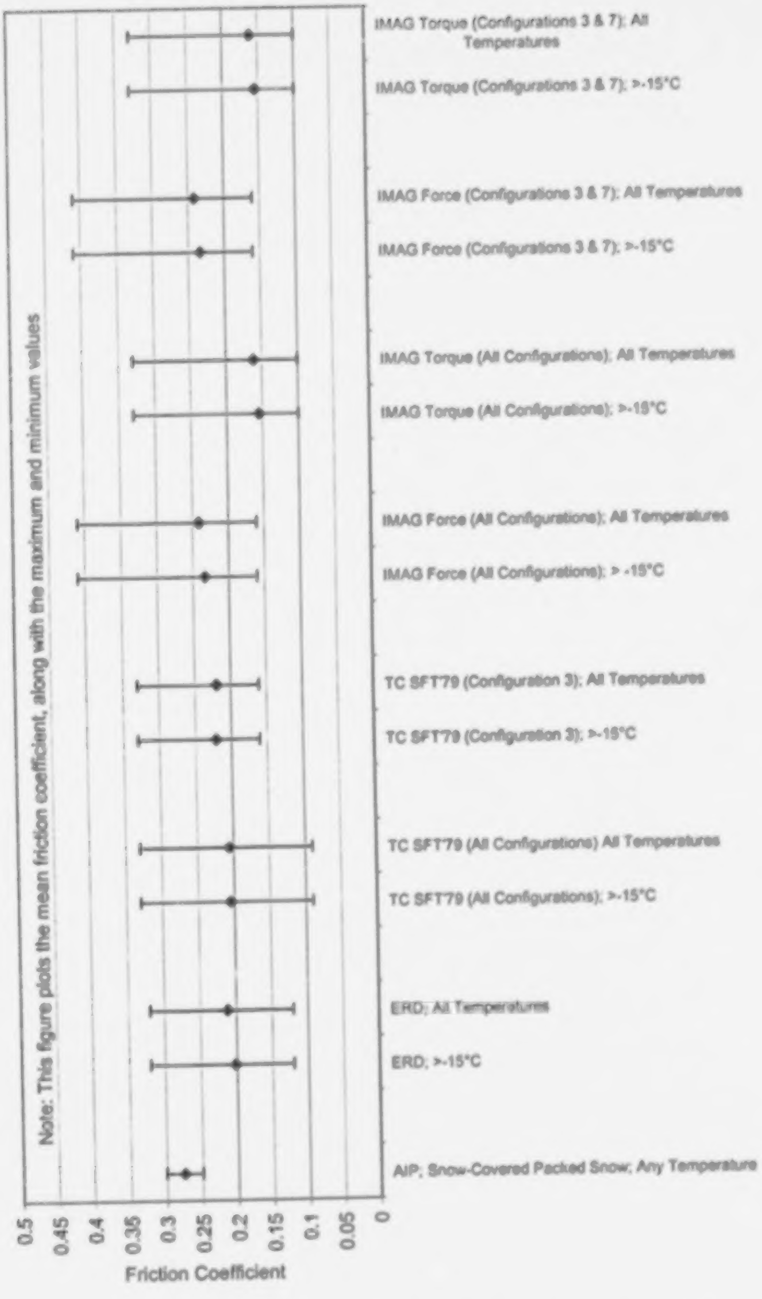


Figure 3.18: Friction Coefficients on Snow Covered Packed Snow (All Depths of Snow Cover): Summary Results

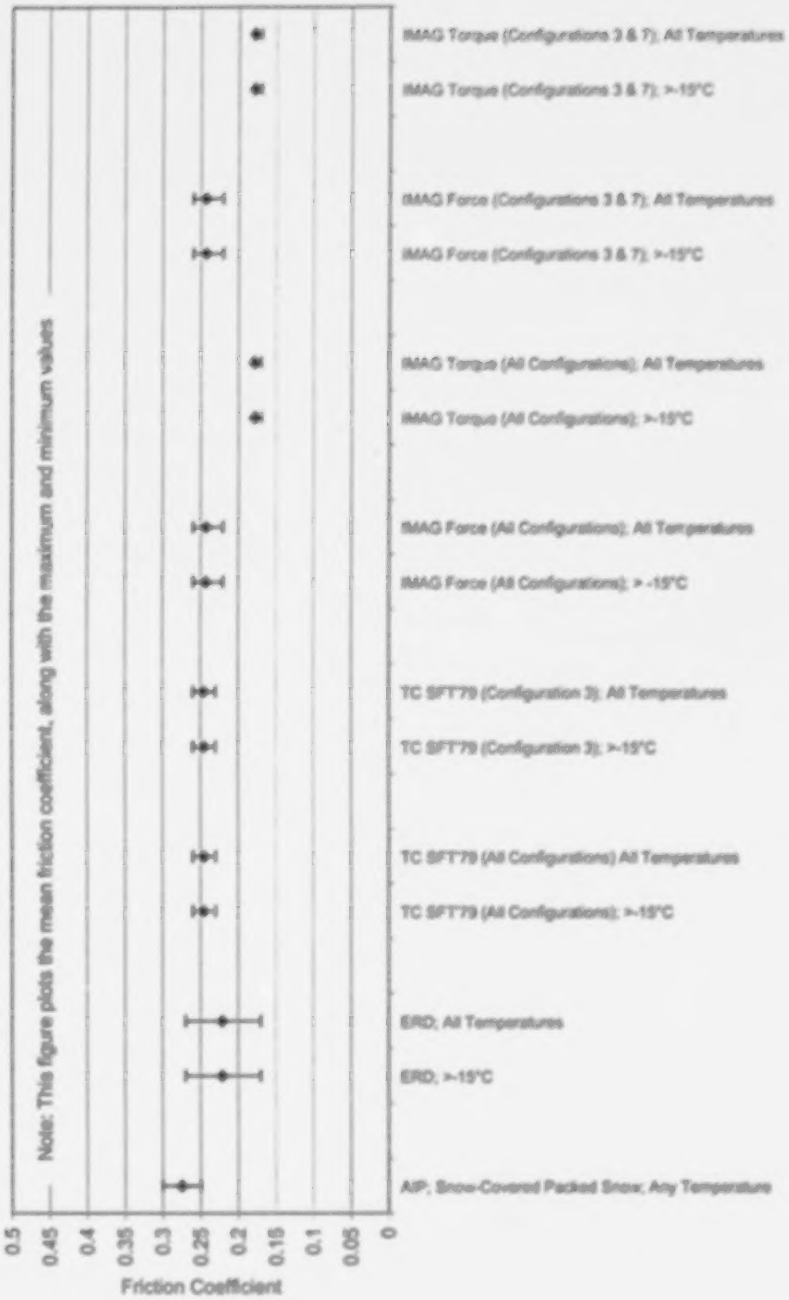


Figure 3.19: Friction Coefficients on Snow Covered Packed Snow (Snow Cover 10 mm or Less Thick): Summary Results

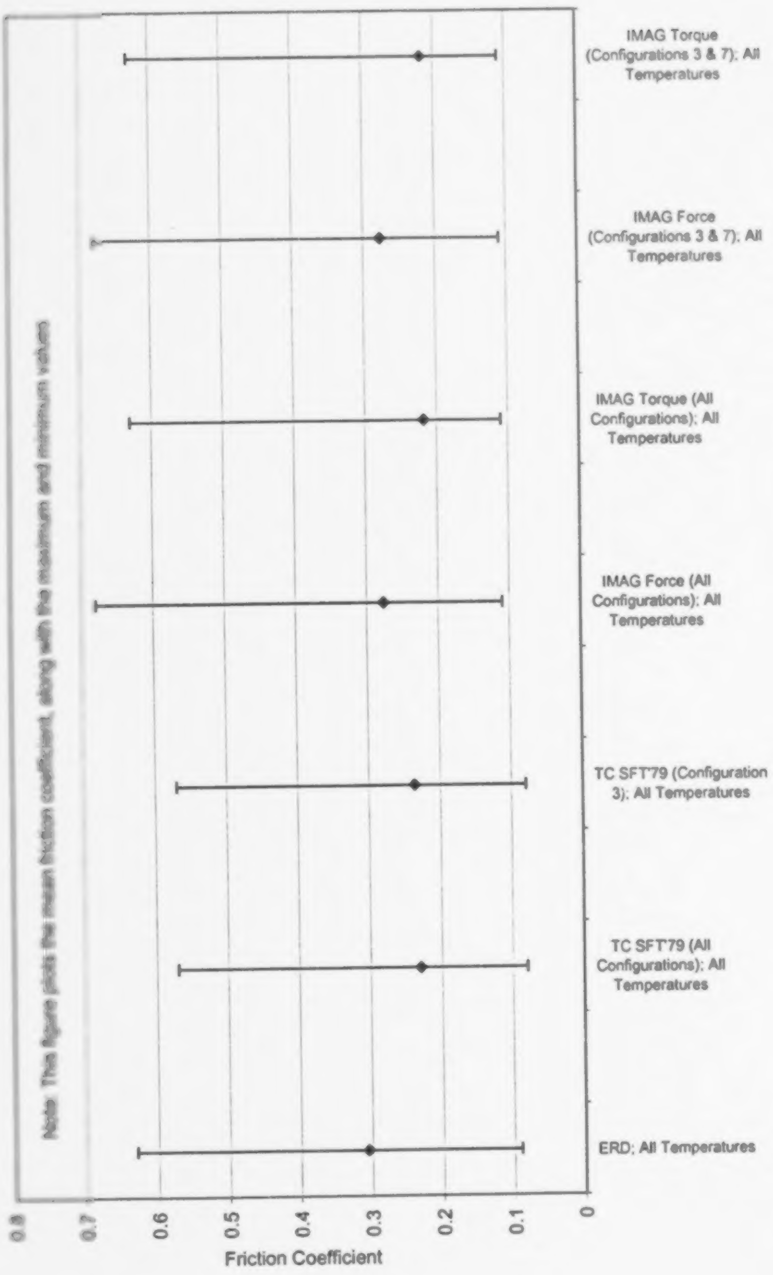


Figure 3.20: Friction Coefficients for Slush on any Base Surface: Summary Results

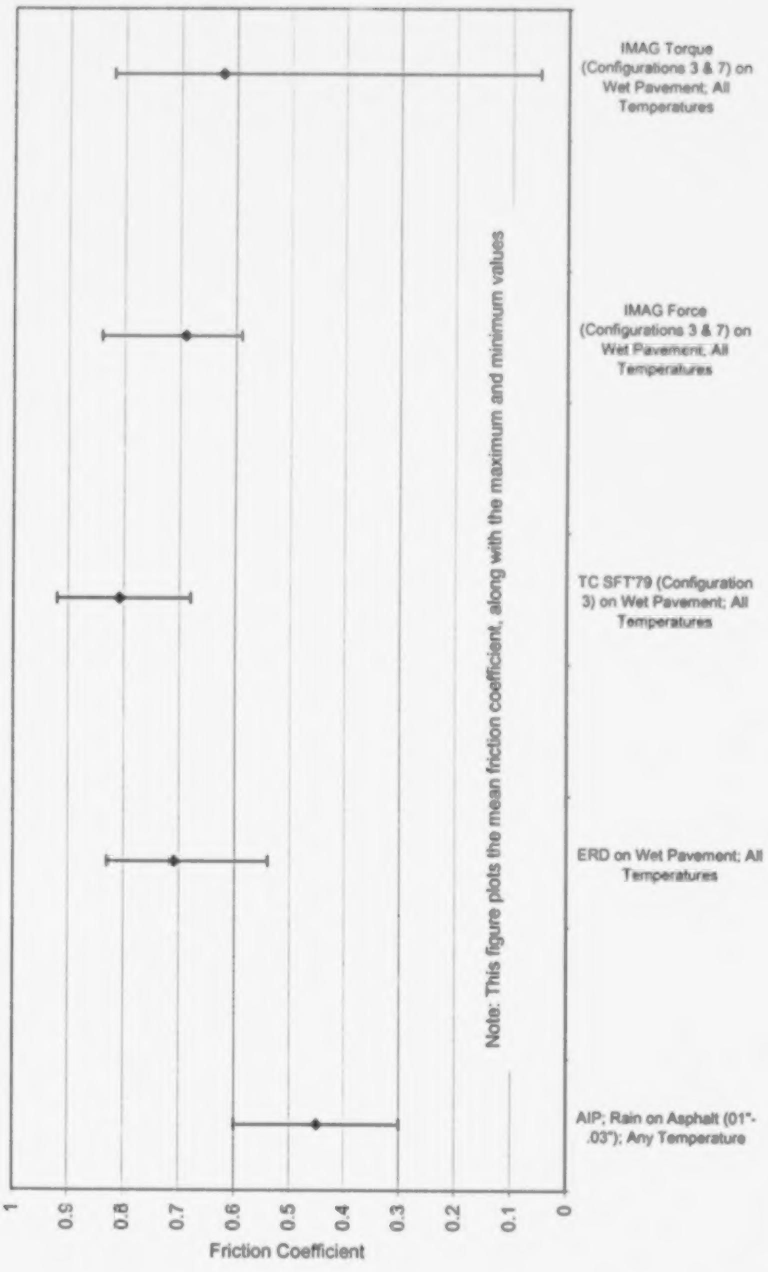
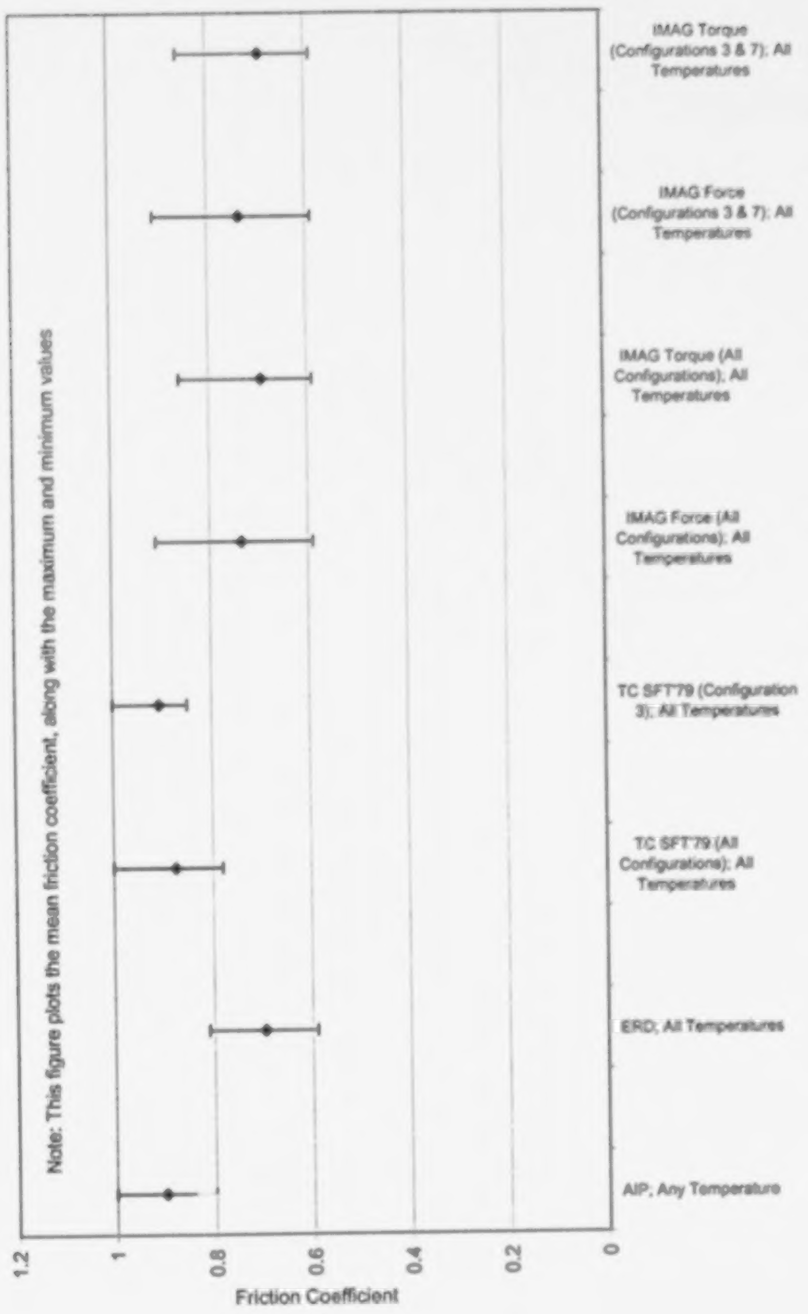


Figure 3.21: Friction Coefficients on Wet Pavement: Summary Results



Note: This figure plots the mean friction coefficient, along with the maximum and minimum values

Figure 3.22: Friction Coefficients on Dry Pavement: Summary Results

4. CORRELATION AMONG DEVICES BY SURFACE TYPE

4.1 Results: ERD vs. TC SFT'79

Figures 4.1, 4.2, and 4.3 show results for all surfaces, bare surfaces only, and contaminated surfaces only, respectively. More detailed plots are contained in Appendix J, showing a breakdown by surface type and base type. General comparisons are shown in Table 4.1.

It is evident that the largest scatter occurs for the contaminated surfaces. Compare Figures 4.2 and 4.3. This probably reflects forces due to contaminant drag that are likely to be more significant for the ERD (as it is a locked-wheel test).

Table 4.1: Summary Comparison: ERD vs. TC SFT'79

Surface Type	Friction Level	Comparison
Bare	All friction levels	TC SFT'79 readings about 10% higher than the ERD ones
Contaminated	Less than about 0.4	• Relationship is highly scattered • Generally, the ERD read higher than did the TC SFT'79
Contaminated	Greater than about 0.4	• Relationship is highly scattered • Generally, the ERD read lower than did the TC SFT'79

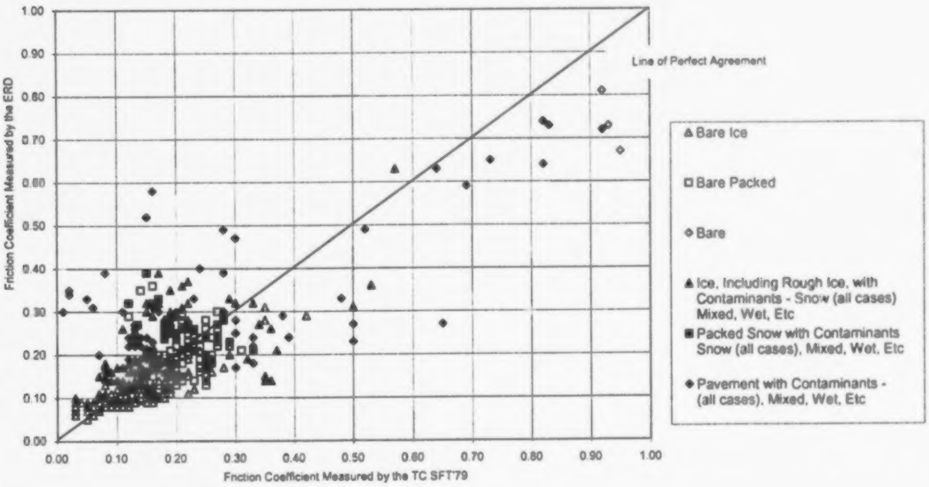


Figure 4.1: Correlation of ERD to TC SFT'79: All Surfaces

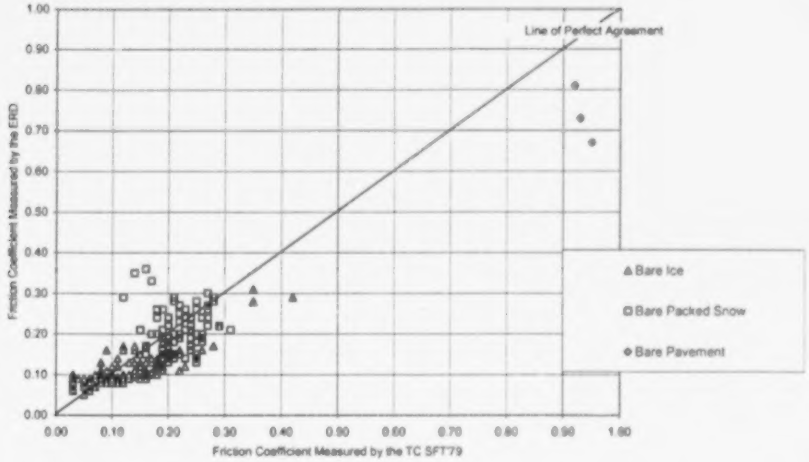


Figure 4.2: Correlation of ERD to TC SFT'79: Bare Surfaces

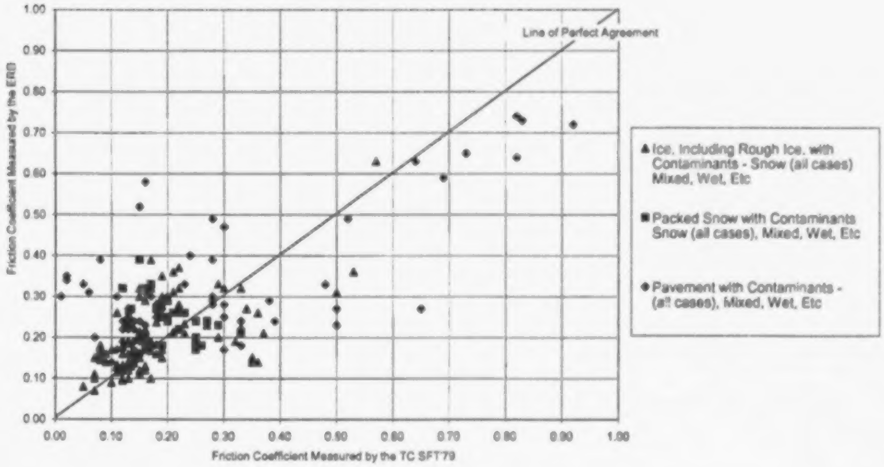


Figure 4.3: Correlation of ERD to TC SFT'79: Contaminated Surfaces

4.2 Results: ERD vs. IMAG Force

Figures 4.4, 4.5, and 4.6 show results for all surfaces, bare surfaces only, and contaminated surfaces only, respectively. More detailed plots are contained in Appendix K, showing a breakdown by surface type and base type. General comparisons are shown in Table 4.2.

As was the case for the TC SFT'79, the largest scatter occurs for the contaminated surfaces. Compare Figures 4.5 and 4.6. This probably reflects forces due to contaminant drag that are likely to be more significant for the ERD (as it is a locked-wheel test).

Table 4.2: Summary Comparison: ERD vs. IMAG Force

Surface Type	Friction Level	Comparison
Bare	All friction levels	IMAG Force readings about 10% higher than the ERD ones
Contaminated	Less than about 0.4	• Relationship is highly scattered • Generally, the ERD read higher than did the IMAG Force
Contaminated	Greater than about 0.4	• Relationship is highly scattered • Generally, the ERD read lower than did the IMAG Force

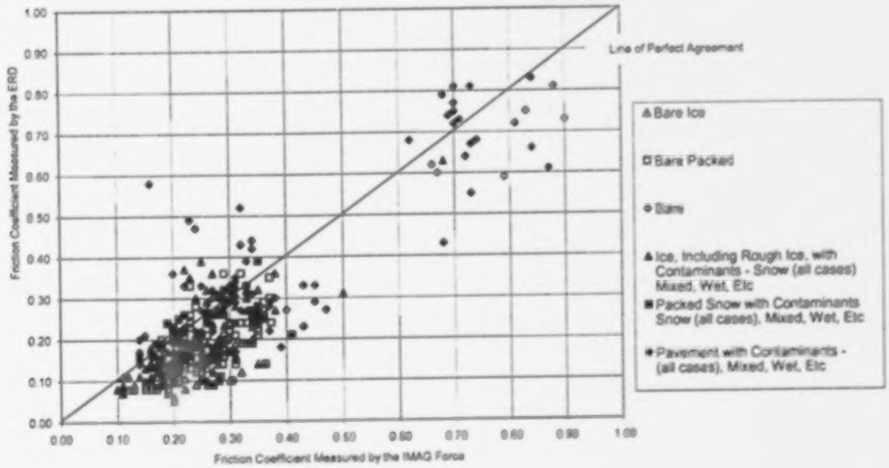


Figure 4.4: Correlation of ERD to IMAG Force: All Surfaces

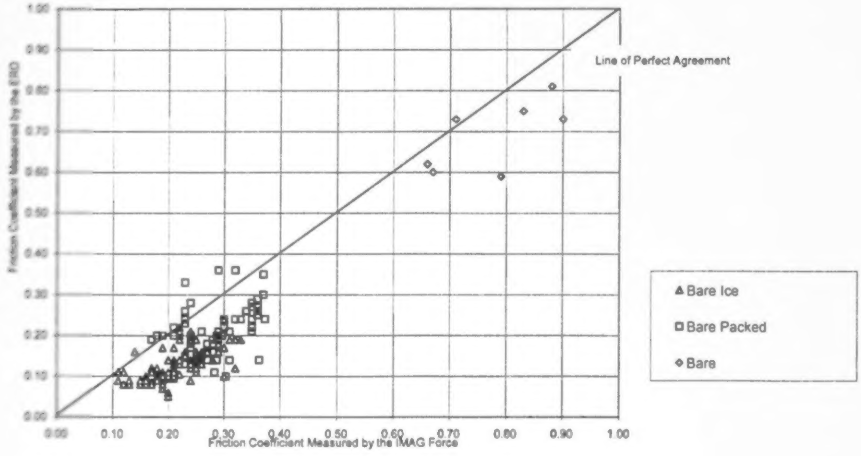


Figure 4.5: Correlation of ERD to IMAG Force: Bare Surfaces

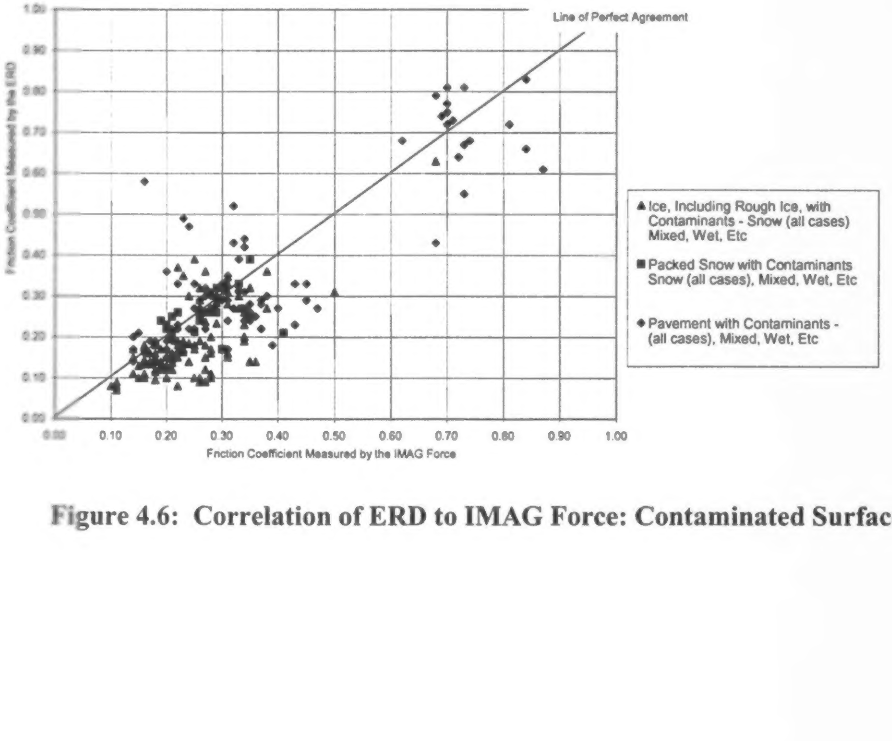


Figure 4.6: Correlation of ERD to IMAG Force: Contaminated Surfaces

4.3 Results: ERD vs. IMAG Torque

Figures 4.7, 4.8, and 4.9 show results for all surfaces, bare surfaces only, and contaminated surfaces only, respectively. More detailed plots are contained in Appendix L, showing a breakdown by surface type and base type. General comparisons are shown in Table 4.3.

As was the case for the other comparisons made to date, the largest scatter occurs for the contaminated surfaces. Compare Figures 4.8 and 4.9. This probably reflects forces due to contaminant drag that are likely to be more significant for the ERD (as it is a locked-wheel test).

Table 4.3: Summary Comparison: ERD vs. IMAG Torque

Surface Type	Friction Level	Comparison
Bare	All friction levels	IMAG Torque readings slightly higher (less than 10%) than the ERD ones
Contaminated	Less than about 0.4	• Relationship is highly scattered • Generally, the ERD read higher than did the IMAG Torque
Contaminated	Greater than about 0.4	• Relationship is highly scattered • Generally, the ERD read lower than did the IMAG Torque

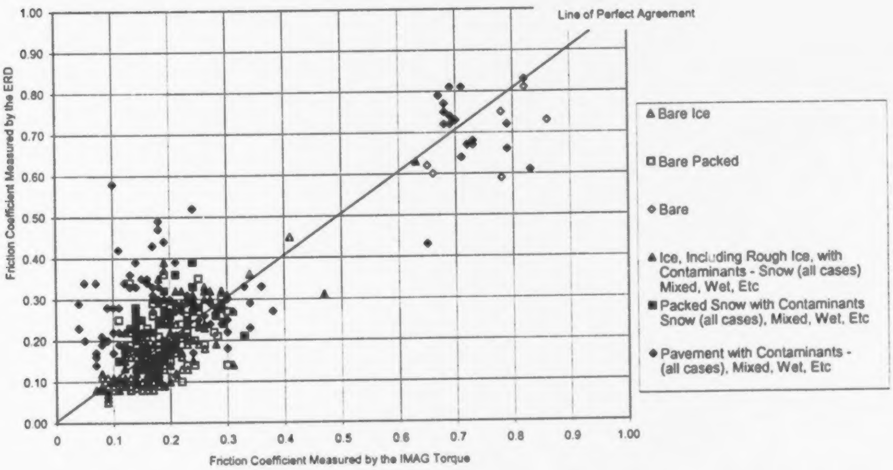


Figure 4.7: Correlation of ERD to IMAG Torque: All Surfaces

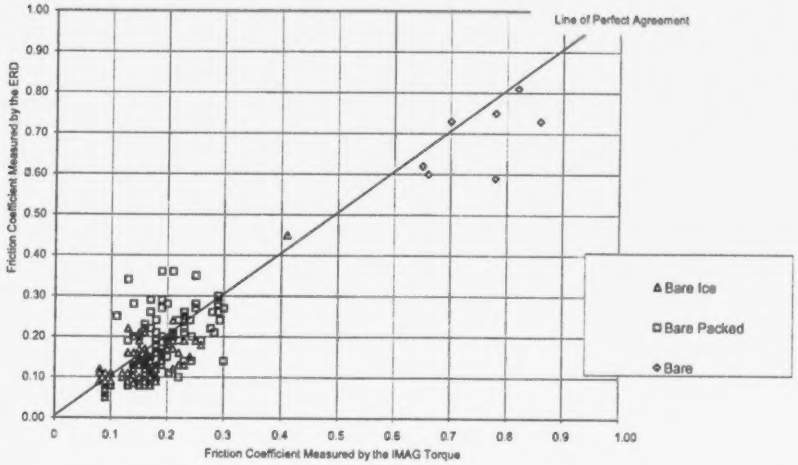


Figure 4.8: Correlation of ERD to IMAG Torque: Bare Surfaces

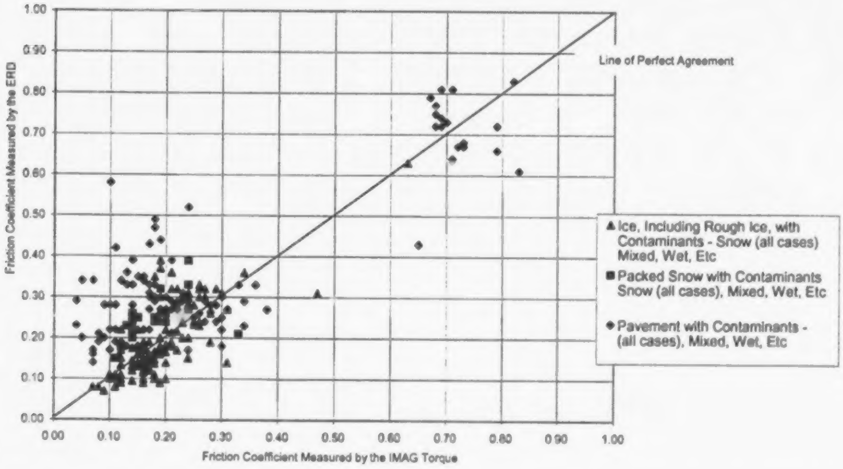


Figure 4.9: Correlation of ERD to IMAG Torque: Contaminated Surfaces

4.4 Results: TC SFT'79 vs. IMAG Force

Figures 4.10, 4.11, and 4.12 show results for all surfaces, bare surfaces only, and contaminated surfaces only, respectively. More detailed plots are contained in Appendix M, showing a breakdown by surface type and base type. General comparisons are shown in Table 4.4.

The scatter is considerably less for this comparison than for all of the ones made with the ERD. Furthermore, the scatter is not significantly different between the contaminated and the bare surfaces. Compare Figures 4.11 and 4.12. This probably reflects the fact that both of these devices utilize a rolling, braked wheel to measure friction, and thus they are better able to "process" contaminants than is the ERD.

Table 4.4: Summary Comparison: TC SFT'79 vs. IMAG Force

Surface Type	Friction Level	Comparison
Bare	Less than about 0.4	IMAG Force readings generally lower than the TC SFT'79 ones
Bare	Greater than about 0.4	IMAG Force readings generally higher than the TC SFT'79 ones
Contaminated	Less than about 0.4	Generally, the TC SFT'79 read higher than did the IMAG Force
Contaminated	Greater than about 0.4	Generally, the TC SFT'79 read lower than did the IMAG Force

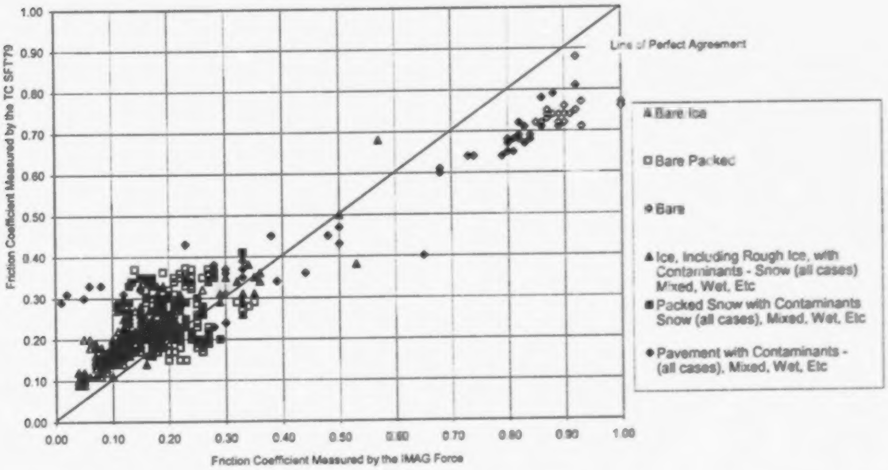


Figure 4.10: Correlation of TC SFT'79 to IMAG Force: All Surfaces

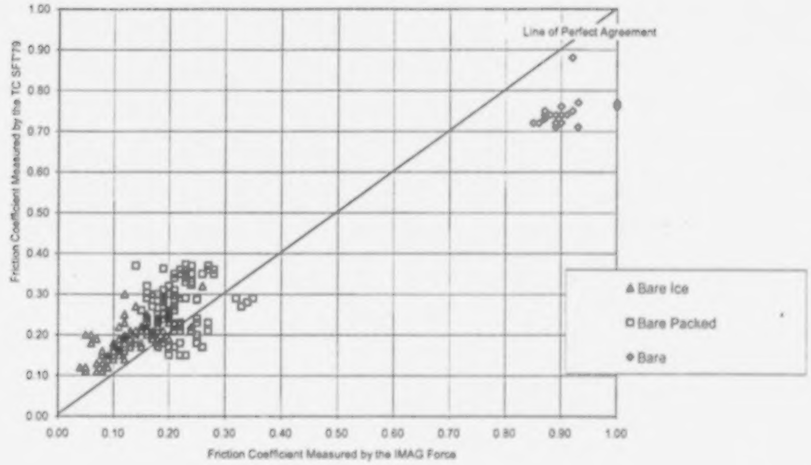


Figure 4.11: Correlation of TC SFT'79 to IMAG Force: Bare Surfaces

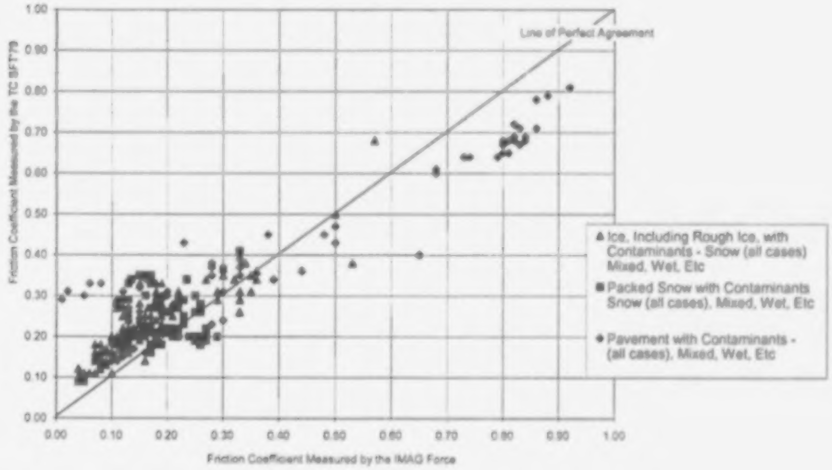


Figure 4.12: Correlation of TC SFT'79 to IMAG Force: Contaminated Surfaces

4.5 Results: TC SFT'79 vs. IMAG Torque

Figures 4.13, 4.14, and 4.15 show results for all surfaces, bare surfaces only, and contaminated surfaces only, respectively. More detailed plots are contained in Appendix N, showing a breakdown by surface and base type. General comparisons are shown in Table 4.5.

As was the case for the IMAG force (section 4.4), the scatter is considerably less for this comparison than for all those made with the ERD. Furthermore, the scatter is not significantly different between the contaminated and the bare surfaces. Compare Figures 4.14 and 4.15. This probably reflects the fact that both of these devices utilize a rolling, braked wheel to measure friction, and thus they are better able to "process" contaminants than is the ERD.

Table 4.5: Summary Comparison: TC SFT'79 vs. IMAG Torque

Surface Type	Friction Level	Comparison
Bare	All friction levels	IMAG Torque readings generally higher than the TC SFT'79 ones
Contaminated	All friction levels	IMAG Torque readings generally higher than the TC SFT'79 ones

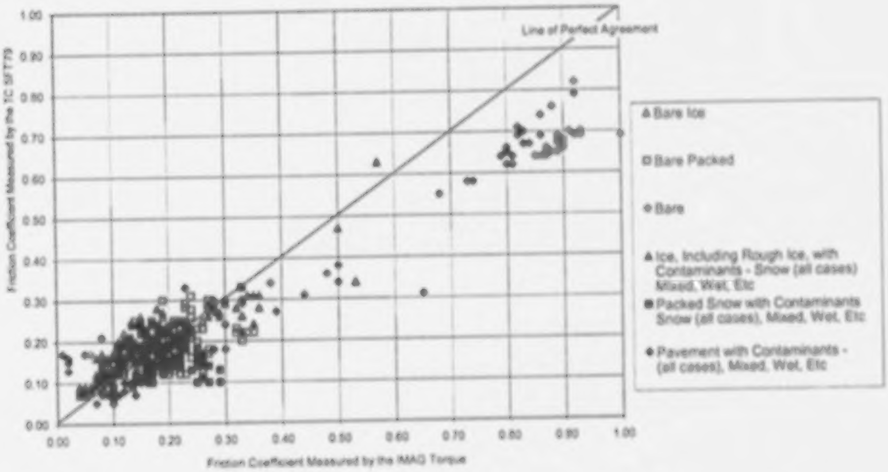


Figure 4.13: Correlation of TC SFT'79 to IMAG Torque: All Surfaces

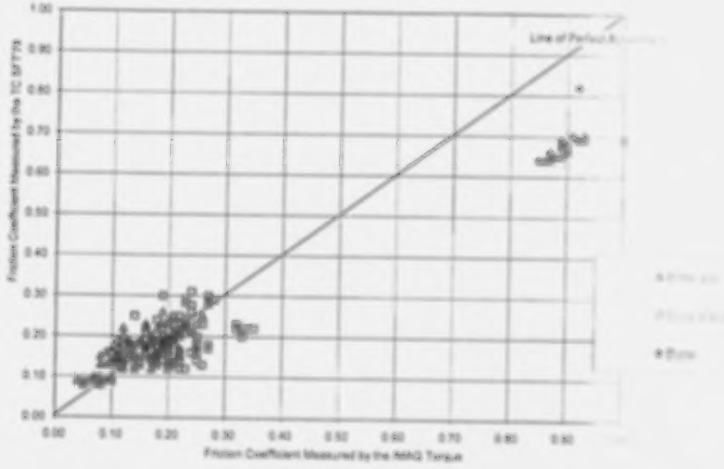


Figure 4.14: Correlation of TC SFT'79 to IMAG Torque: Bare Surfaces

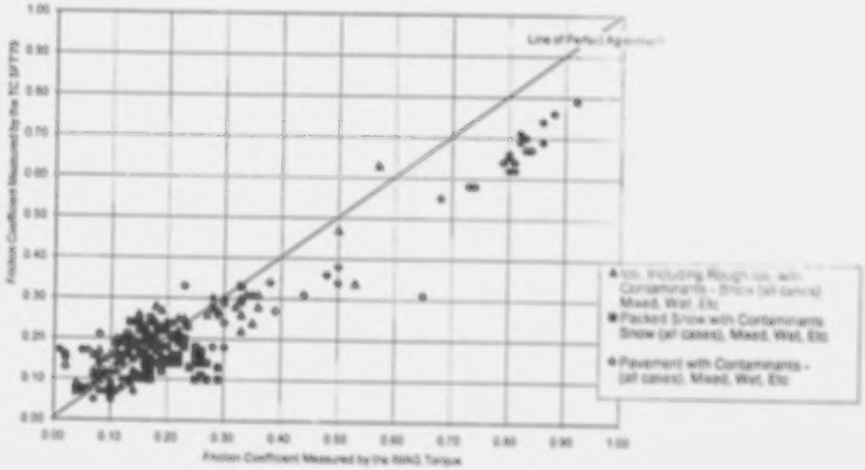


Figure 4.15: Correlation of TC SFT'79 to IMAG Torque: Contaminated Surfaces

4.6 Results: IMAG Force vs. IMAG Torque

Figures 4.16, 4.17, and 4.18 show results for all surfaces, bare surfaces only, and contaminated surfaces only, respectively. More detailed plots are contained in Appendix O, showing a breakdown by surface type and base type. General comparisons are shown in Table 4.6. This comparison showed the least scatter, probably because:

(a) IMAG Force and IMAG Torque are both part of the same device.
(b) IMAG utilizes a rolling, braked wheel to measure friction, which allows it to "process" contaminants. This is probably the reason the scatter is not significantly different between the contaminated and the bare surfaces. Compare Figures 4.17 and 4.18.

Table 4.6: Summary Comparison: IMAG Force vs. IMAG Torque

Surface Type	Friction Level	Comparison
Bare	All friction levels	IMAG Torque readings always lower than the IMAG Force ones
Contaminated	All friction levels	IMAG Torque readings always lower than the IMAG Force ones

It is also evident that:

(a) IMAG Force and IMAG Torque are highly correlated to each other.
(b) The IMAG Force reading is always higher than the IMAG Torque one. This is to be expected as the IMAG Force reading is determined by adding the contaminant drag to the horizontal braking forces applied to the measuring wheel. It is noteworthy that the relationship between the IMAG Torque and IMAG Force is generally similar for both the bare and the contaminated surfaces. (Figures 4.17 and 4.18). This suggests that the contaminant drag is an important part of the total horizontal forces applied to the measuring wheel even for the bare surfaces.

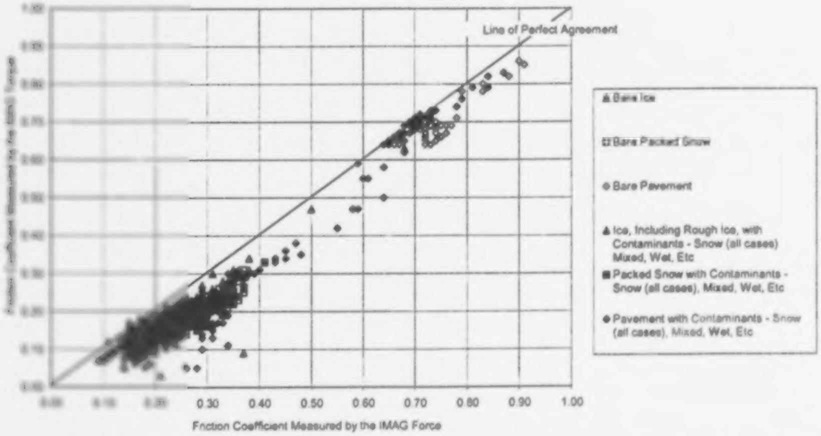


Figure 4.16: Correlation of IMAG Force to IMAG Torque: All Surfaces

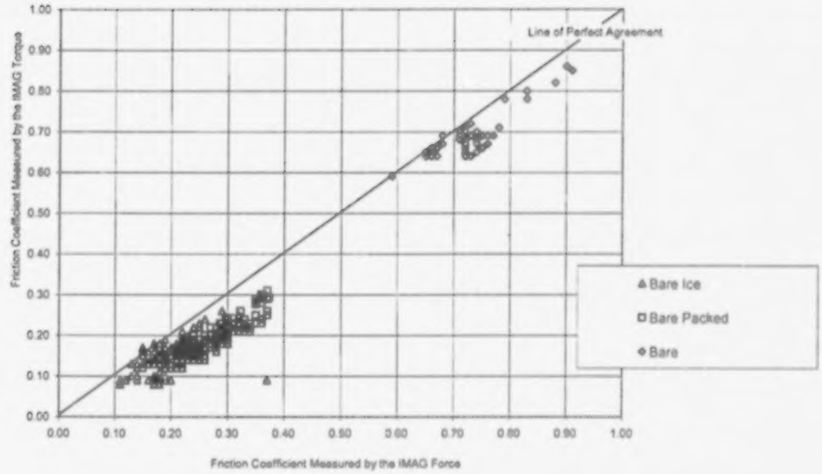


Figure 4.17: Correlation of IMAG Force to IMAG Torque: Bare Surfaces

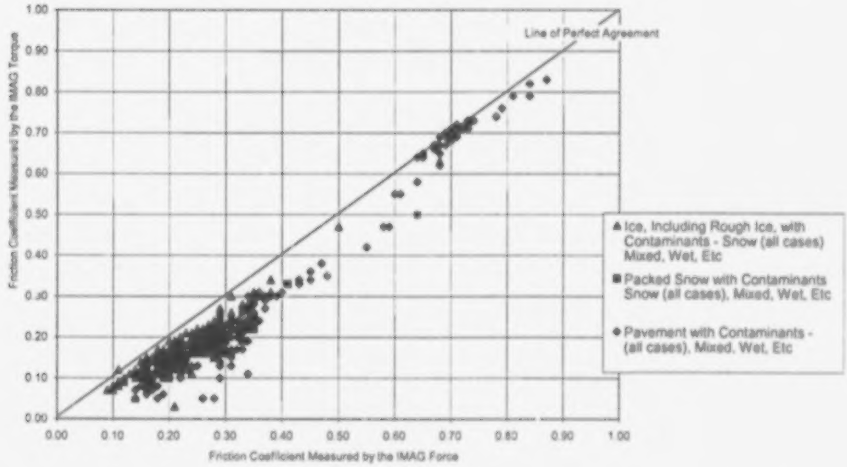


Figure 4.18: Correlation of IMAG Force to IMAG Torque: Contaminated Surfaces

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The results obtained from the JWRFMP were used to investigate the effect of surface conditions on the friction coefficient measured by the ERD, the TC SFT'79, and the IMAG. Two types of analyses were conducted as follows:

(a) Analyses for individual surfaces – Where possible, the friction coefficients obtained from the devices were compared to the guideline CRFIs given in the AIP.
(b) Correlations among the devices.

5.1.1 Analyses for Individual Surfaces

The results varied from device to device and from surface to surface, which makes it difficult to infer general conclusions.

It was commonly observed that the ranges of values observed in the JWRFMP were larger than those given in the AIP.

5.1.2 Correlations among the Devices

The results varied from device to device and from surface to surface, which makes it difficult to infer general conclusions.

It was noted that:

(a) ERD readings on contaminated surfaces were generally higher and more scattered on contaminated surfaces than those for the TC SFT'79 and the IMAG. This probably reflects the fact that the ERD is locked-wheel test.
(b) TC SFT'79 and the IMAG showed good correlation for all surfaces.

5.2 Recommendations

This was an exploratory project that was aimed at investigating general trends and relationships. The results obtained here should be followed up with more detailed quantitative analyses to investigate issues such as:

(a) Variability among the results for different surfaces.

(b) Degree of confidence that one could have in friction coefficients inferred solely from surface descriptions, in comparison to data obtained with friction-measuring devices.

REFERENCES

[1] Comfort, G., and Trott, B., 2002, *Joint Winter Runway Friction Test Program Database Manual*, prepared by Fleet Technology Limited for the Transportation Development Centre on behalf of Aerodrome Safety Branch of Civil Aviation, Transport Canada.

[2] AIP, 2002, *Aeronautical Information Publication*, Air 1-15, Table 4, TP 2300.

[3] Comfort, G., and Gong, Y., 1998, *Analysis of the Friction Factors Measured by the Ground Vehicles at the 1998 North Bay Trials*, TP 13366E Transportation Development Centre, Transport Canada.

APPENDIX A

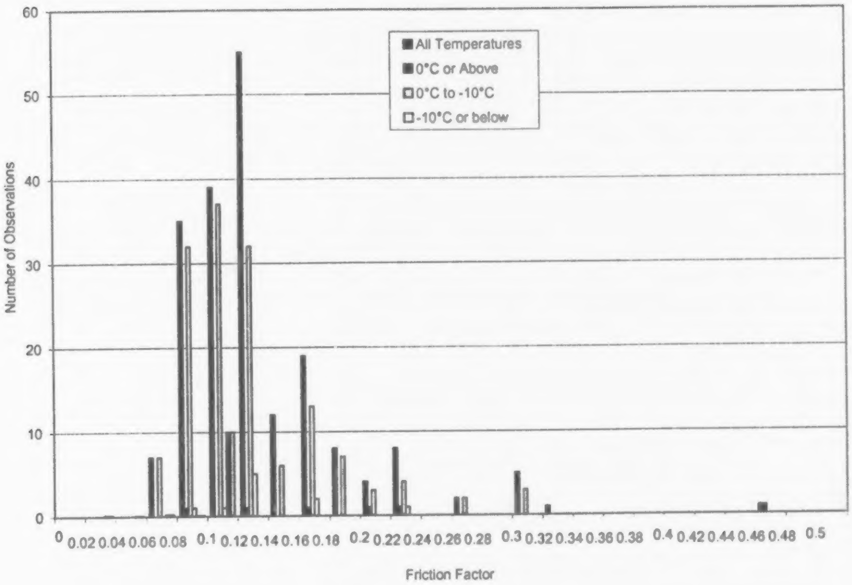
RESULTS FOR BARE ICE

Contents

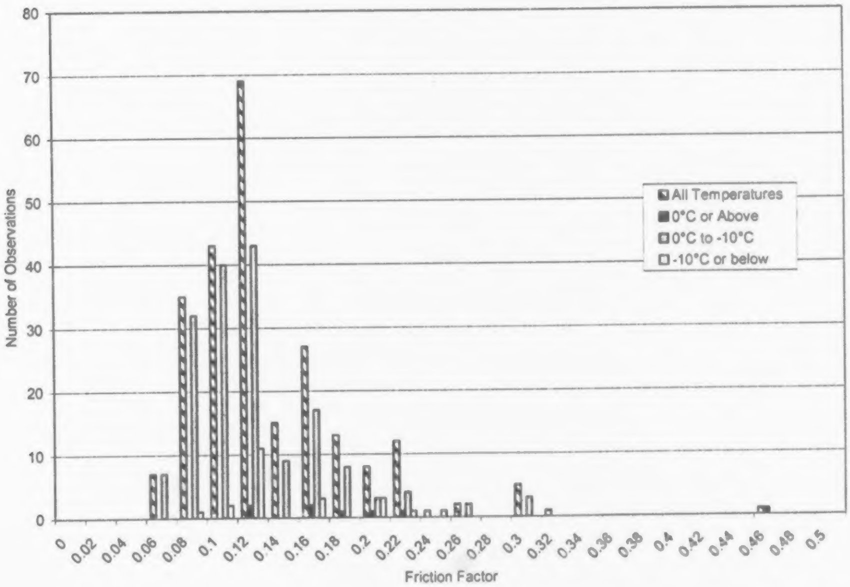
Appendix A.1: Histograms
Appendix A.2: Trend Plots vs. Surface Temperature

APPENDIX A.1

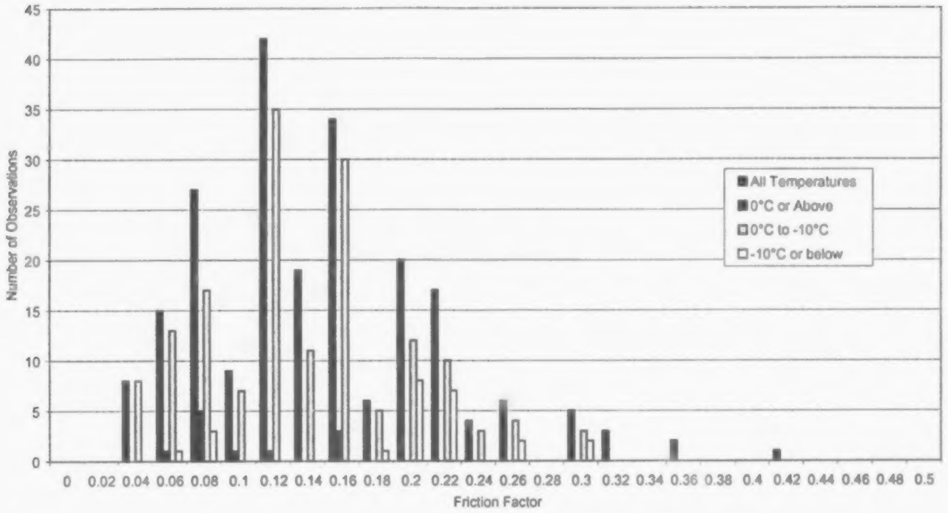
HISTOGRAMS



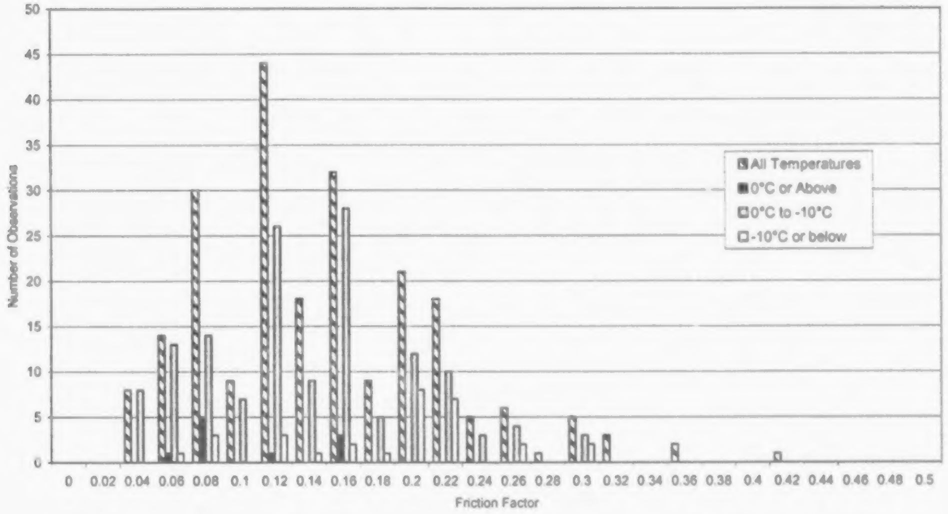
A.1-1: ERD Readings on Bare Ice: Effect of Temperature



A.1-2: ERD Readings on Bare Ice and Rough Ice: Effect of Temperature



A.1-3: ERD TC SFT'79 (All Configurations) Readings on Bare Ice: Effect of Temperature



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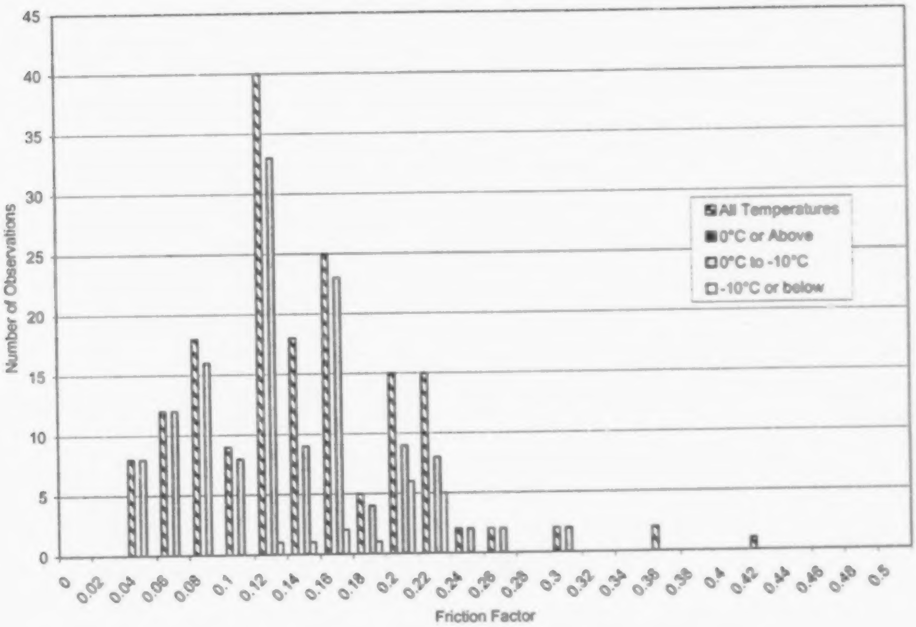
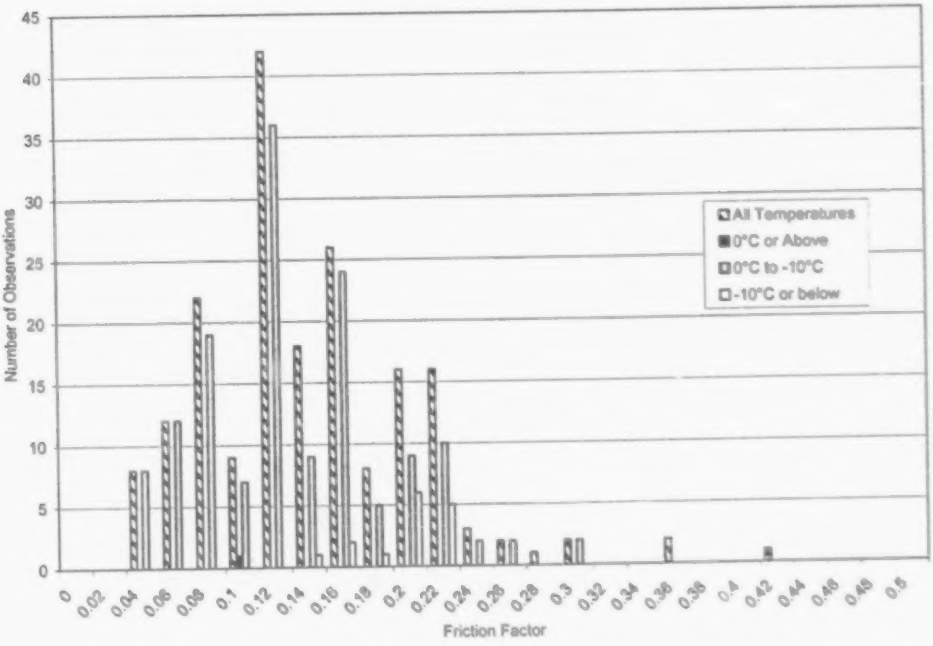


A.1-5: TC SFT'79 (Configuration 3) Readings on Bare Ice: Effect of Temperature



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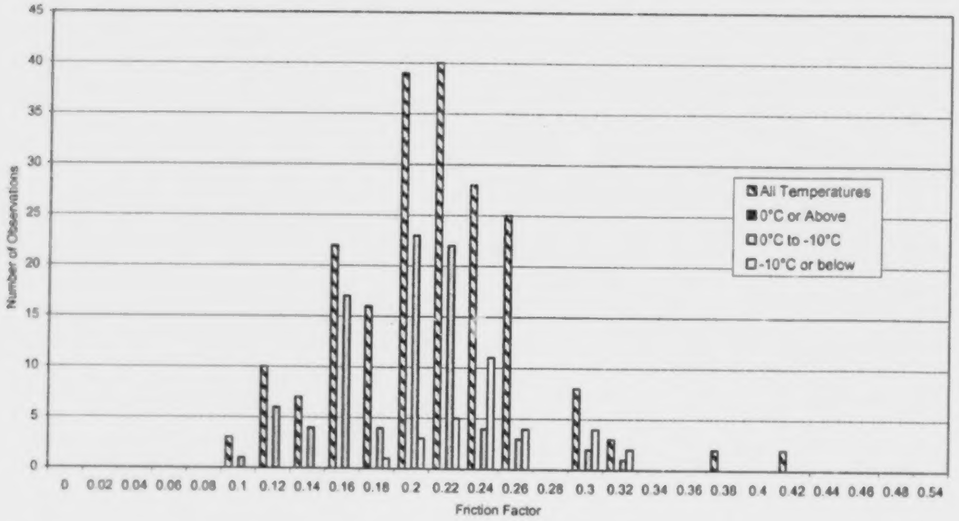
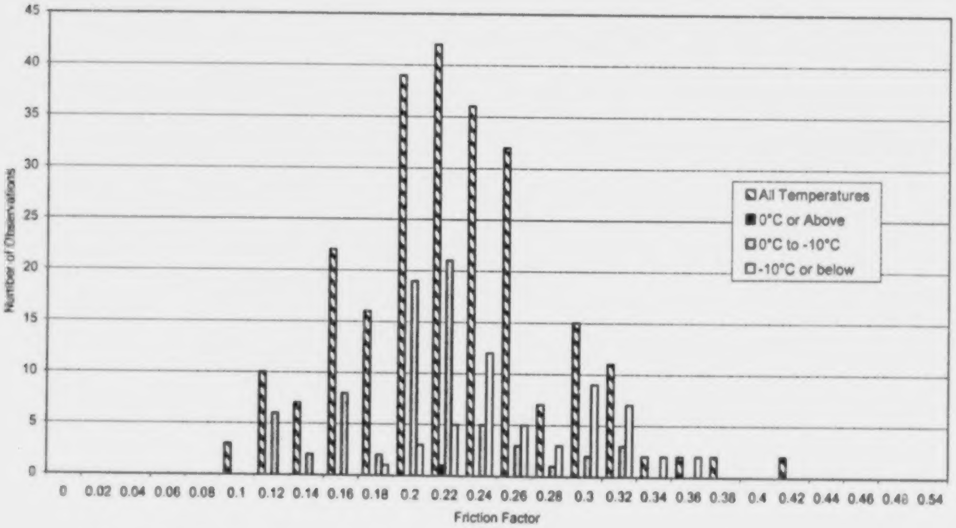
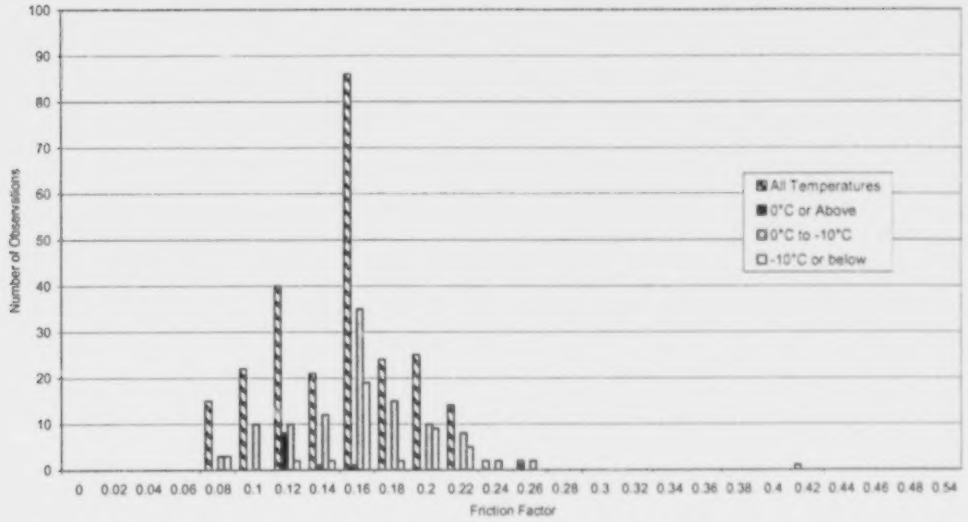


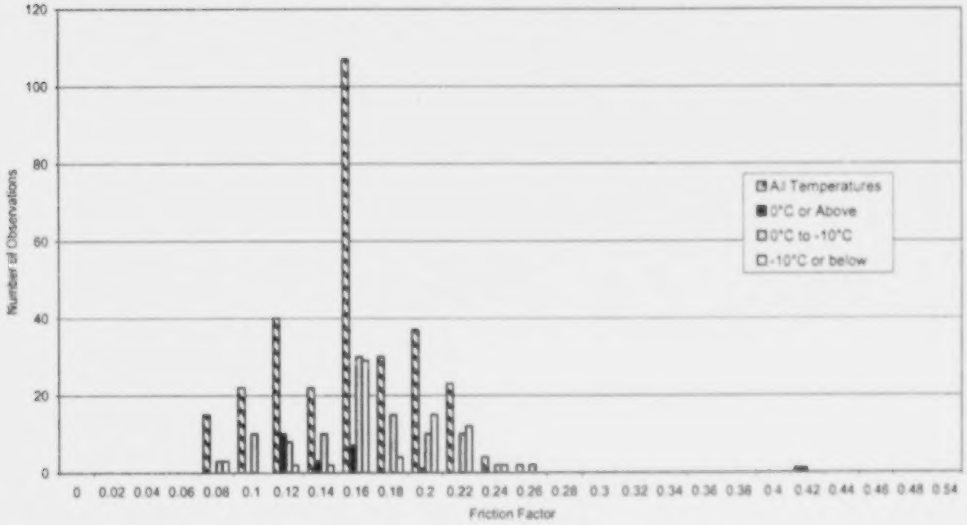
A.1-7: IMAG Force (All Configurations) Readings on Bare Ice: Effect of Temperature



A.1-8: IMAG Force (All Configurations) Readings on Bare and Rough Ice: Effect of Temperature



A.1-9: IMAG Torque (All Configurations) Readings on Bare Ice: Effect of Temperature



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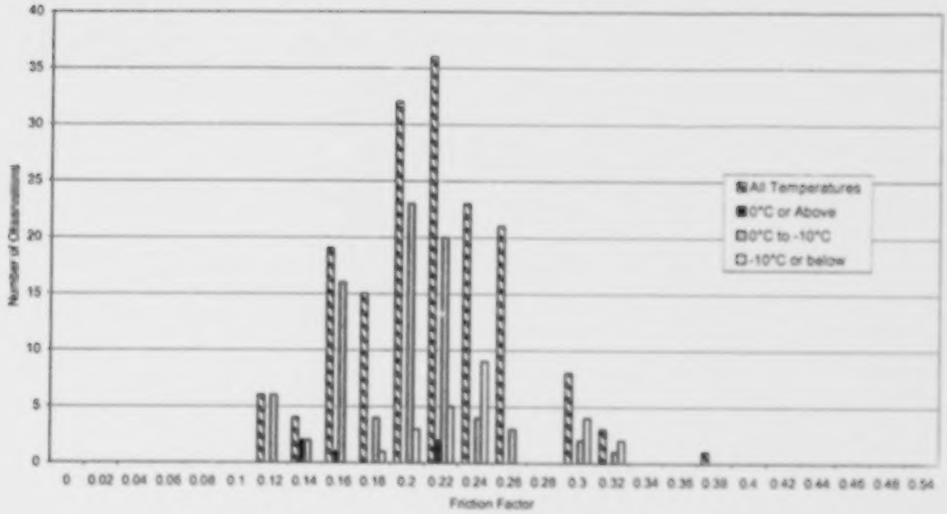
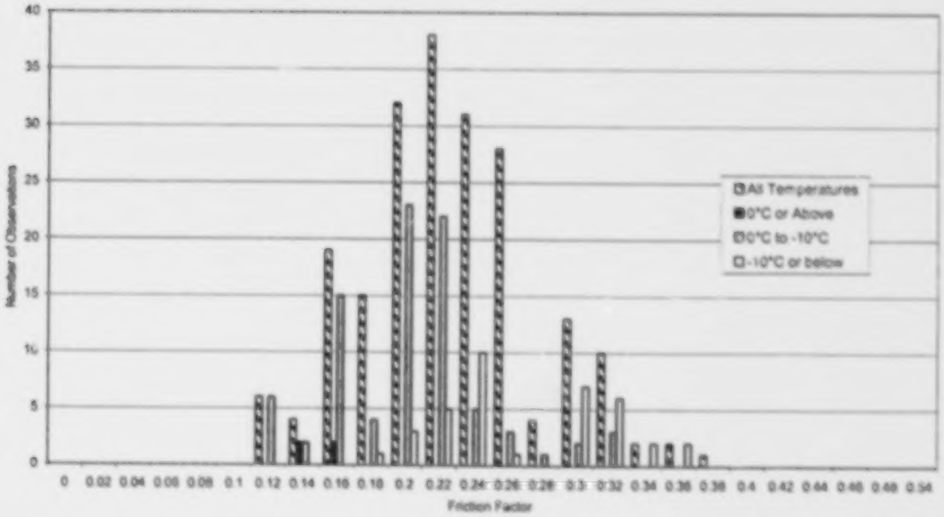


A.1-11: IMAG Force (Configurations 3 and 7) Readings on Bare Ice: Effect of Temperature



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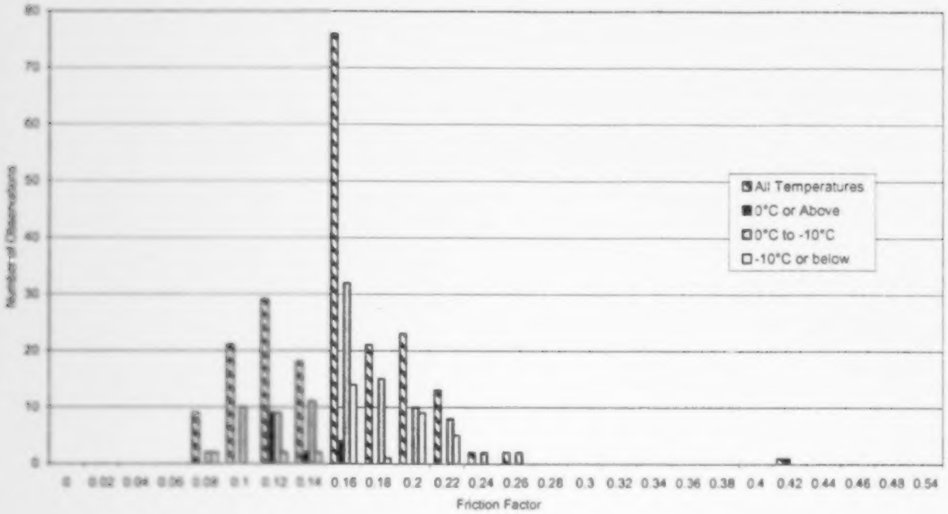

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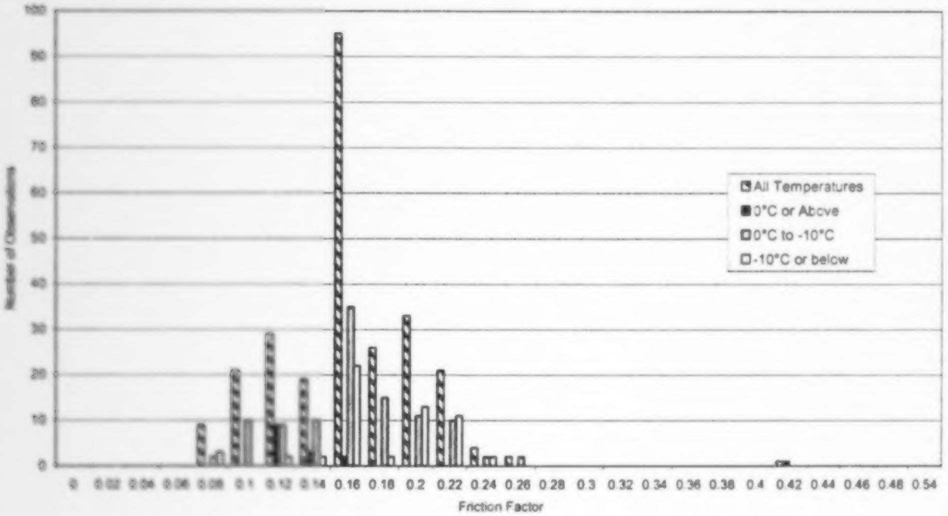
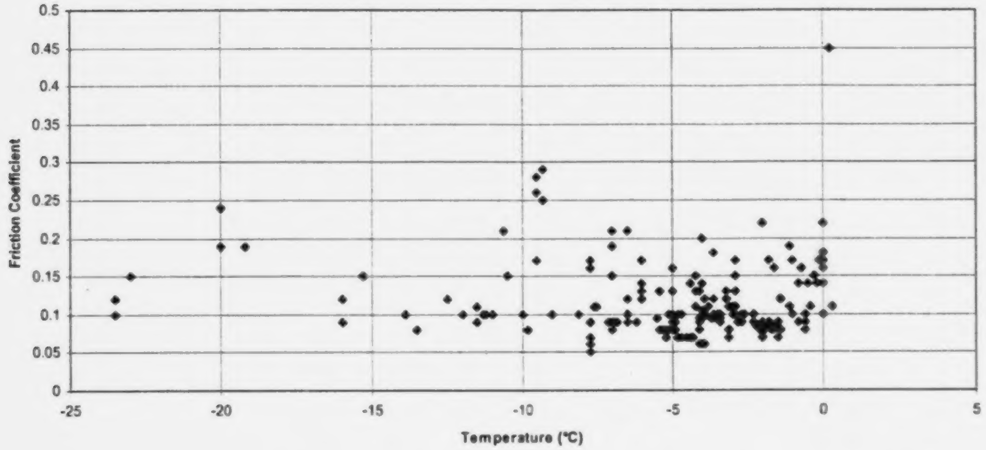


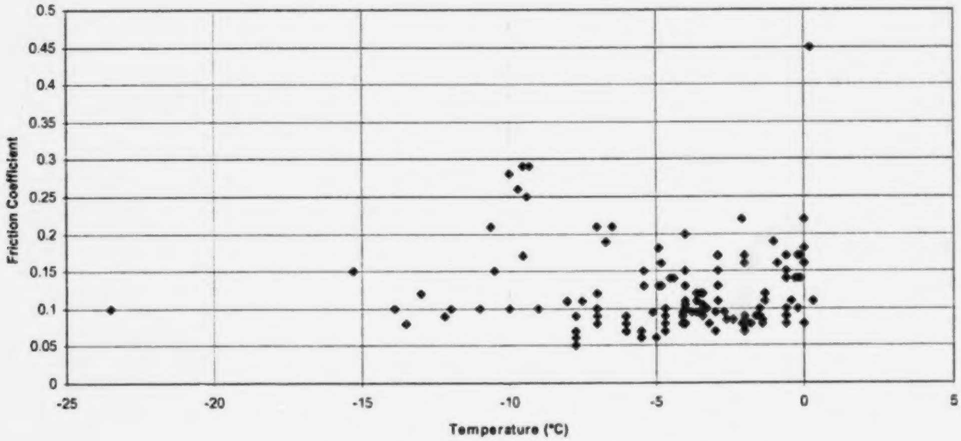
A.1-14: IMAG Force (Configurations 3 and 7) Readings on Bare and Rough Ice: Effect of Temperature

APPENDIX A.2

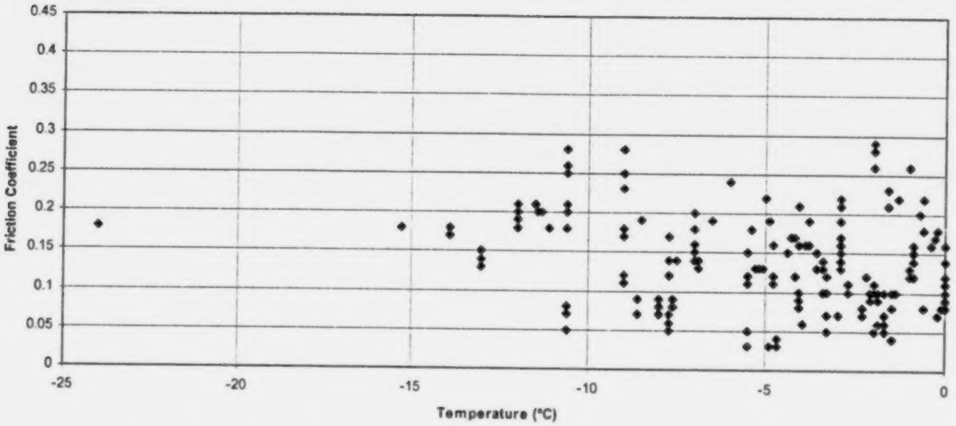
TREND PLOTS VS. SURFACE TEMPERATURE



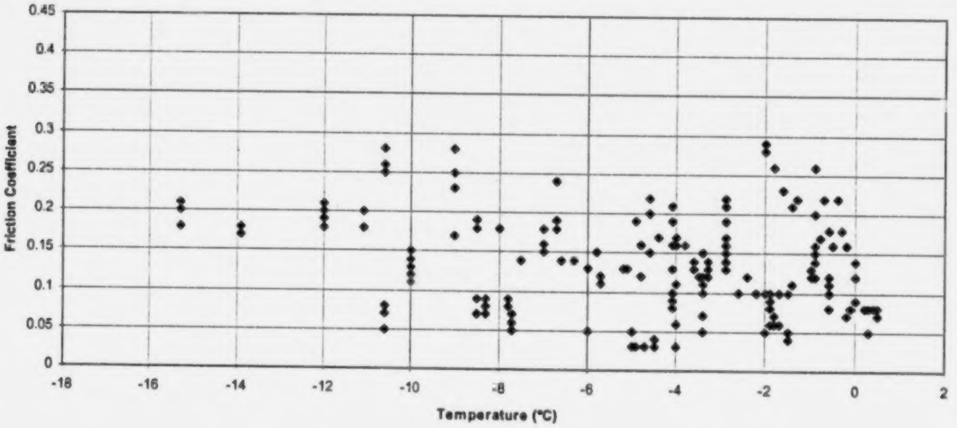
A.2-1: Effect of Temperature: ERD Readings on Bare Ice and Rough Ice



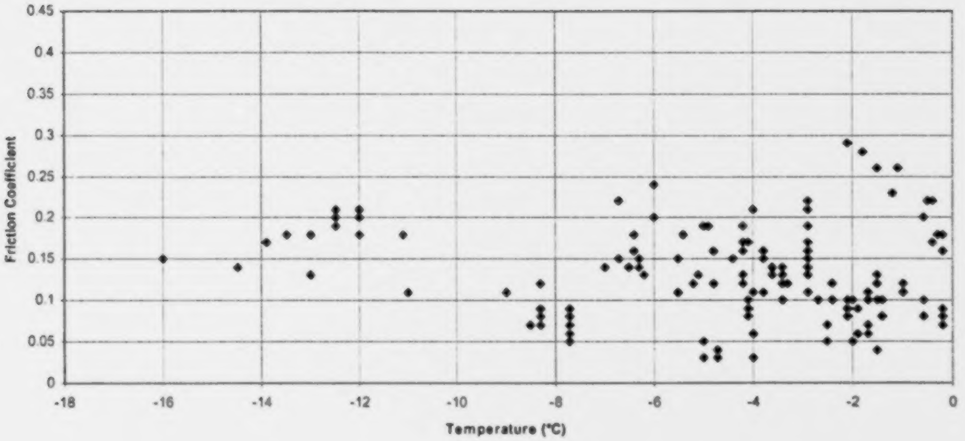
A.2-2: Effect of Temperature: ERD Readings on Bare Ice



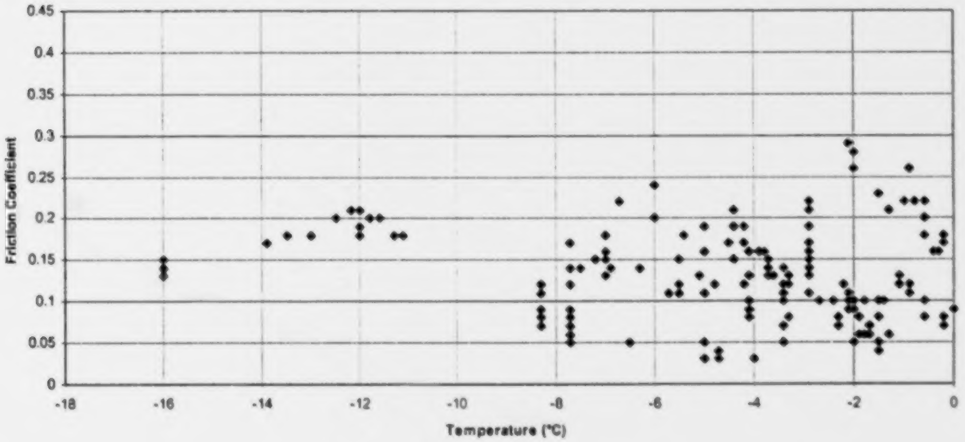
A.2-3: Effect of Temperature: TC SFT'79 (All Configurations)
Readings on Bare and Rough Ice



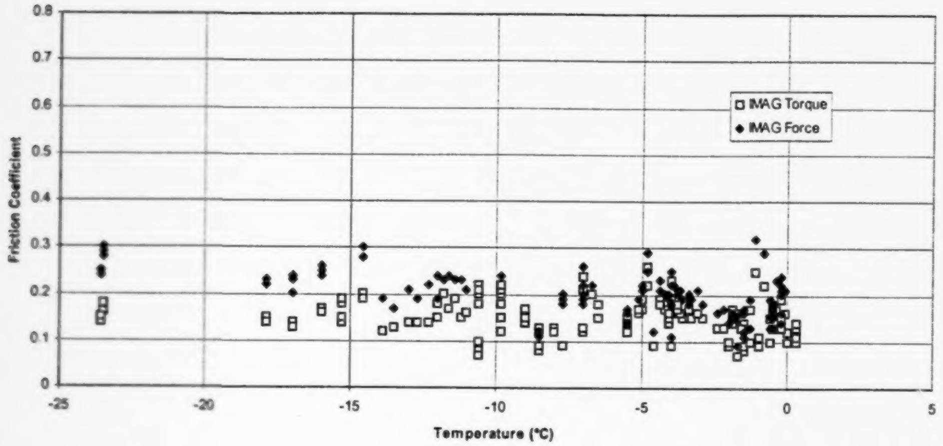
A.2-4: Effect of Temperature: TC SFT'79 (All Configurations)
Readings on Bare Ice



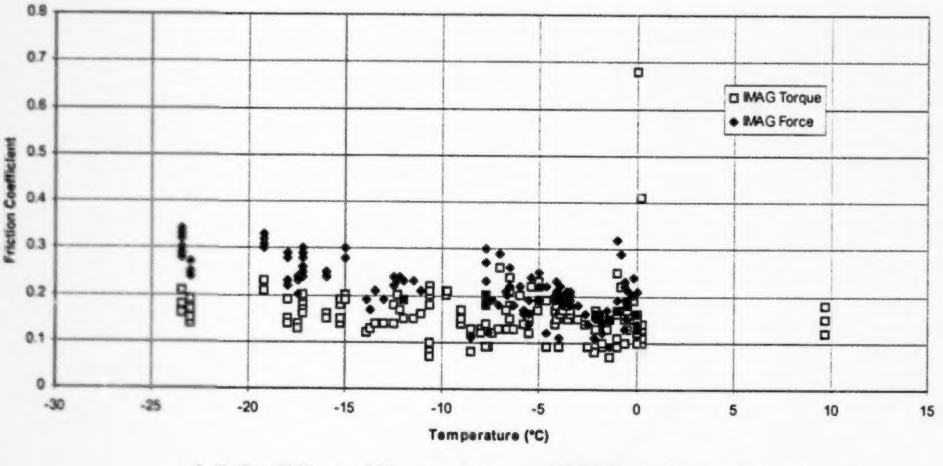
A.2-5: Effect of Temperature: TC SFT'79 (Configuration 3) Readings on Bare Ice



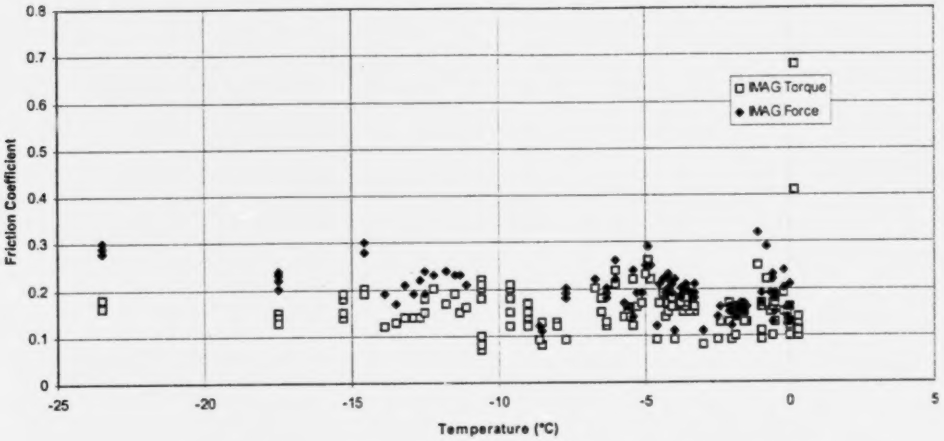
A.2-6: Effect of Temperature: TC SFT'79 (Configuration 3) Readings on Bare and Rough Ice



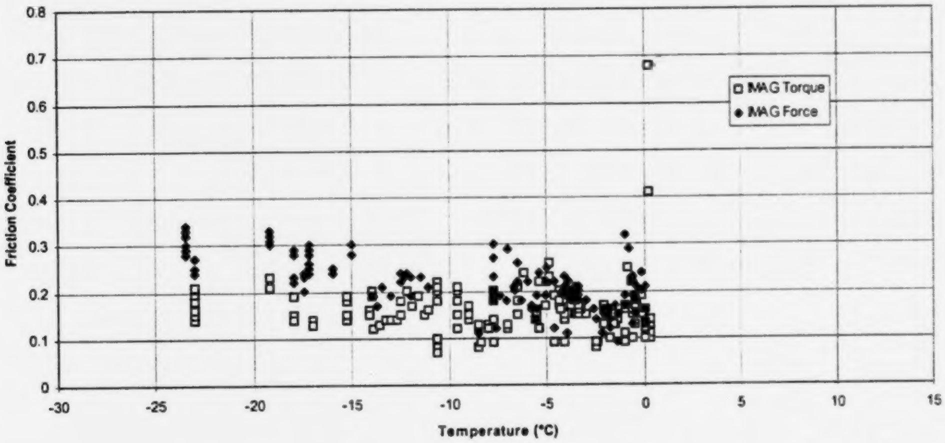
A.2-7: Effect of Temperature: IMAG (All Configurations) Readings on Bare Ice



A.2-8: Effect of Temperature: IMAG (All Configurations) Readings on Bare and Rough Ice



A.2-9: Effect of Temperature: IMAG (Configurations 3 and 7) Readings on Bare Ice



A.2-10: Effect of Temperature: IMAG (Configurations 3 and 7) Readings on Bare and Rough Ice

APPENDIX B

RESULTS FOR BARE PACKED SNOW

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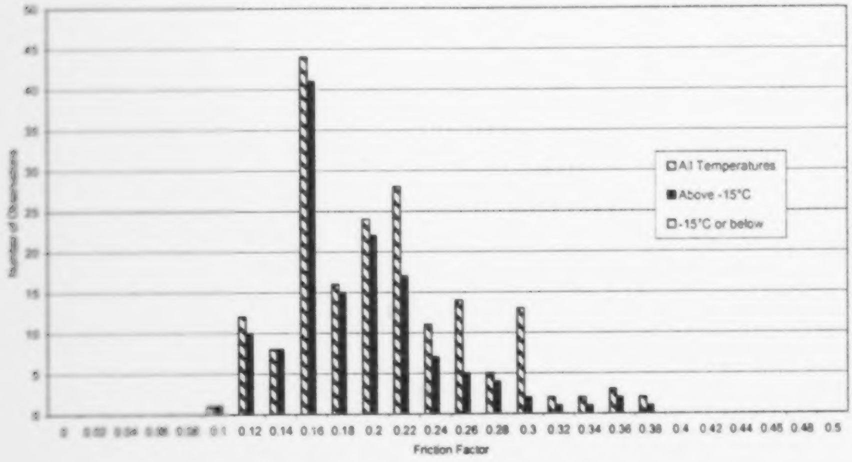
Appendix B.2: Trend Plots vs. Surface Temperature

APPENDIX B.1

HISTOGRAMS



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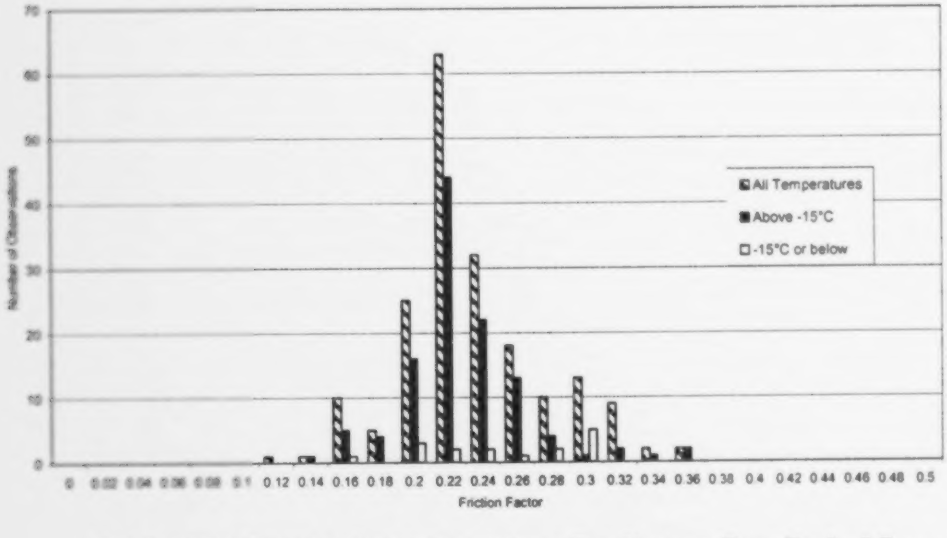
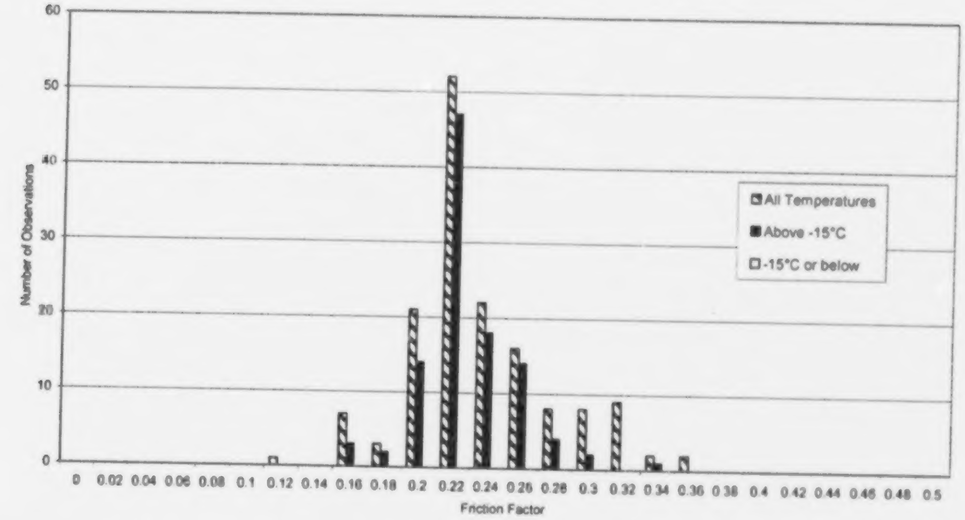


B.1-2: TC SFT'79 (All Configurations) Readings on Bare Packed Snow: Effect of Temperature



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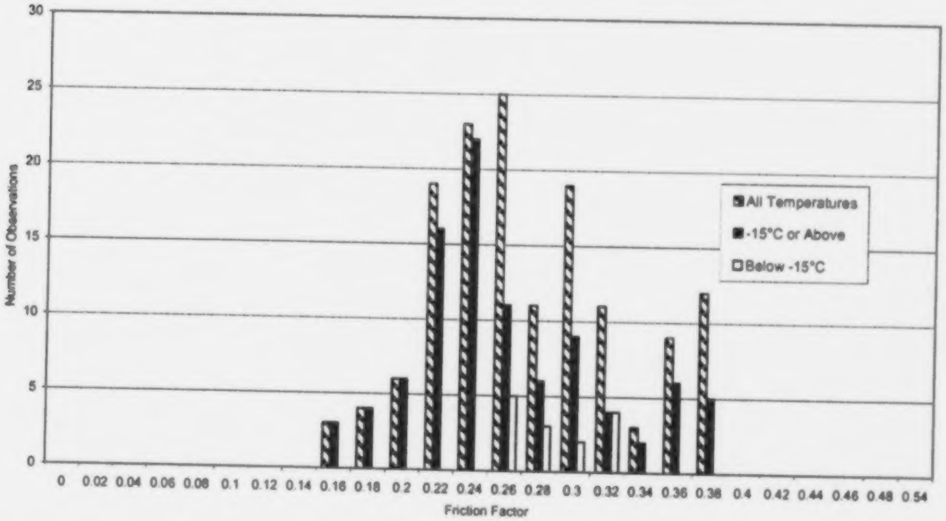

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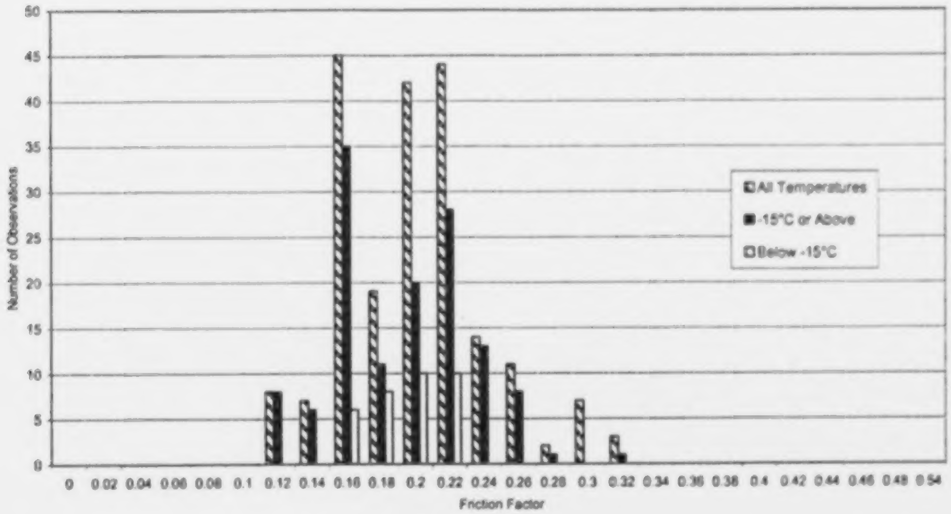

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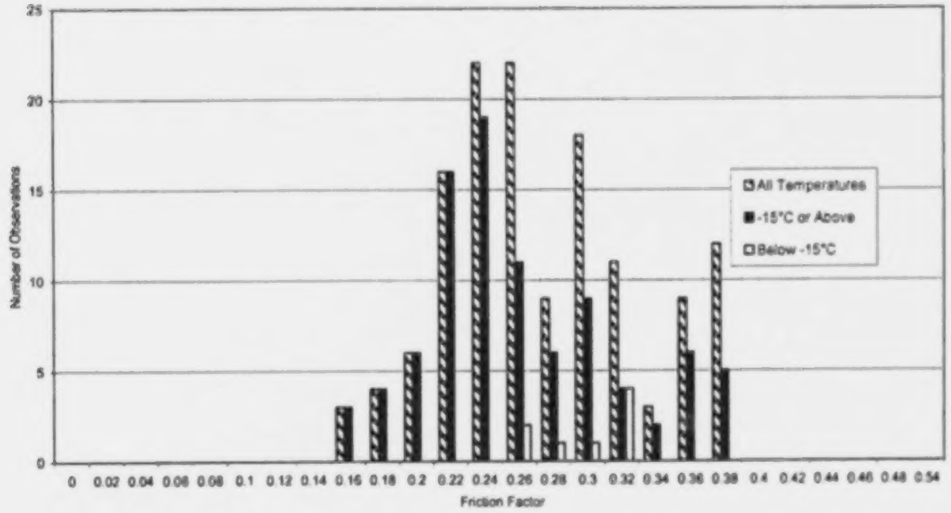
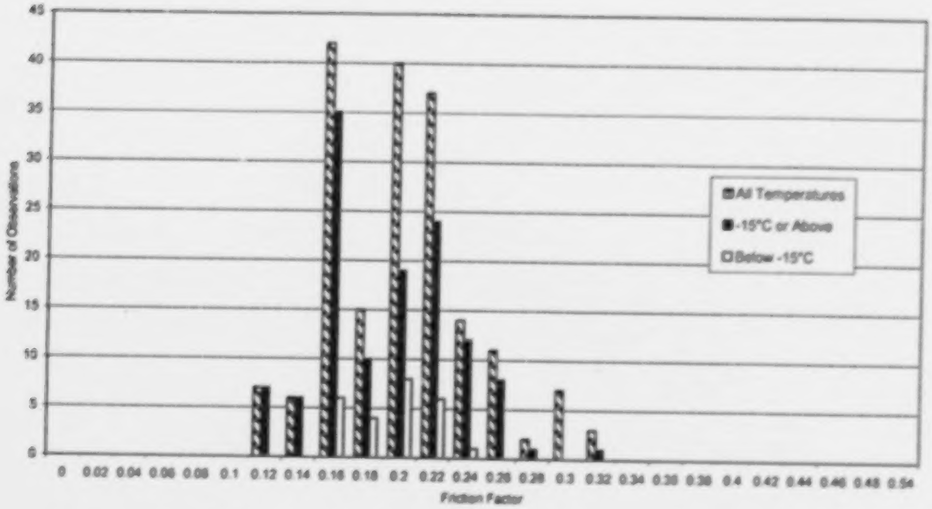


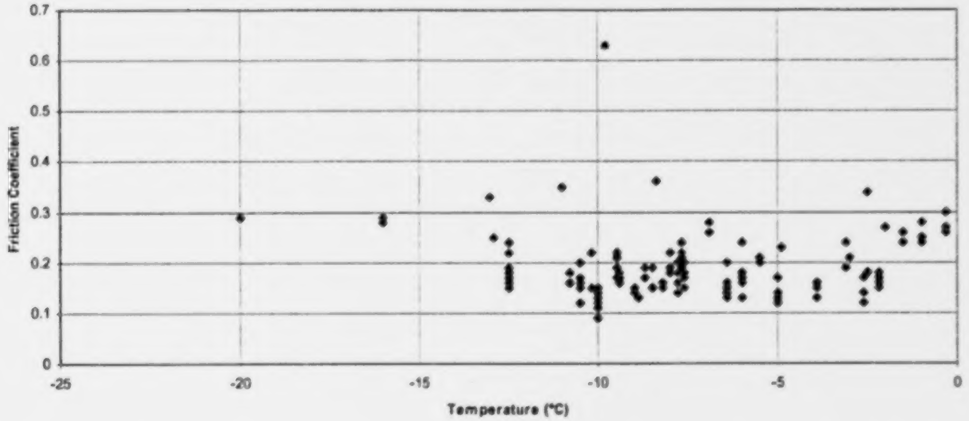
B.1-6: IMAG Forces (Configurations 3 and 7) Readings on Bare Packed Snow: Effect of Temperature



B.1-7: IMAG Forces (Configurations 3 and 7) Readings on Bare Packed Snow: Effect of Temperature

APPENDIX B.2

TREND PLOTS VS. SURFACE TEMPERATURE



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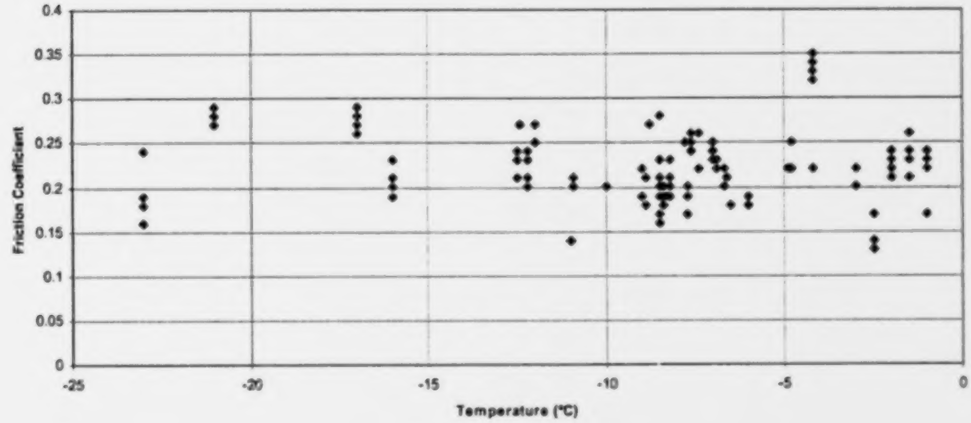
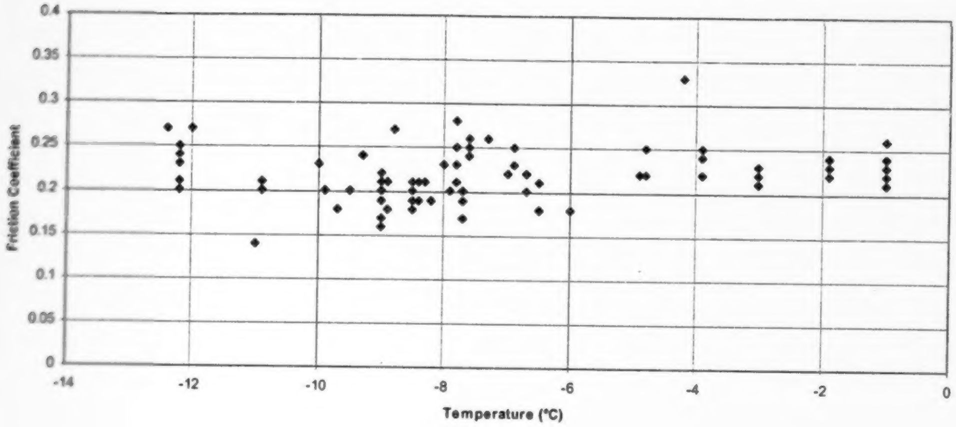


B.2-2: Effect of Temperature: TC SFT'79 (All Configurations) Readings on Bare Packed Snow



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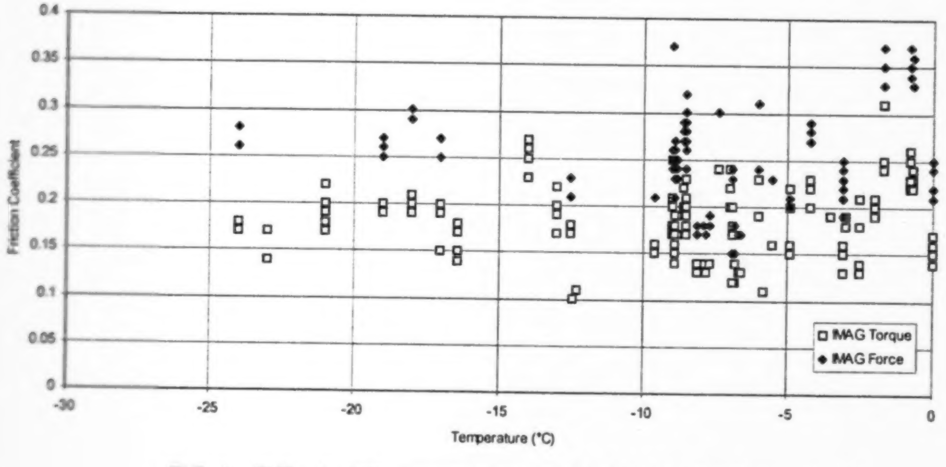
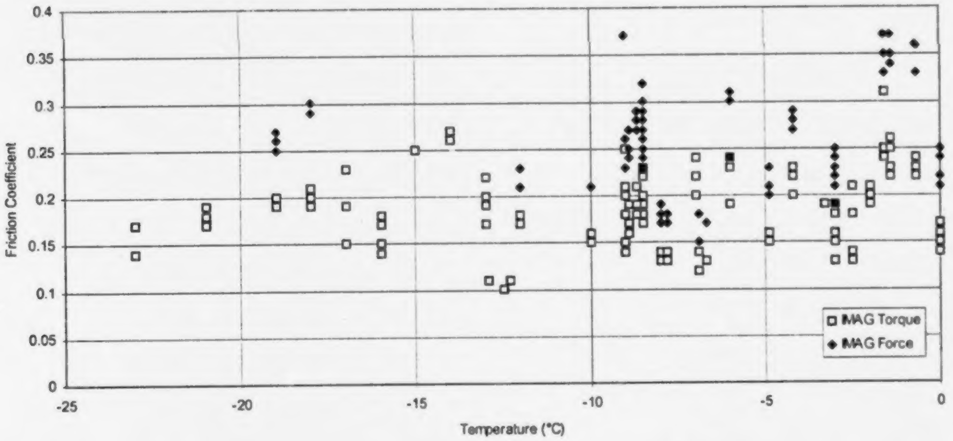


B.2-4: Effect of Temperature: IMAG (All Configurations) Readings on Bare Packed Snow



B.2-5: Effect of Temperature: IMAG (Configurations 3 and 7) Readings on Bare Packed Snow

APPENDIX C

RESULTS FOR SANDED BARE ICE

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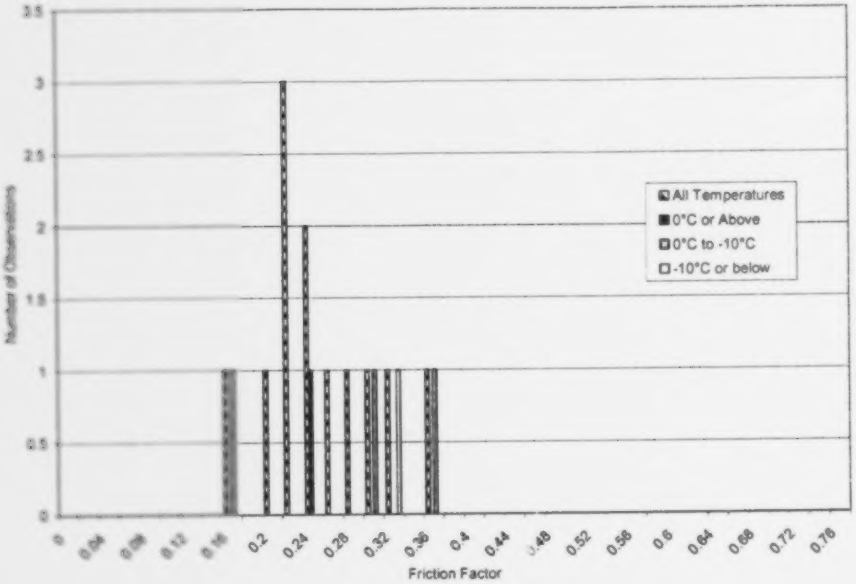
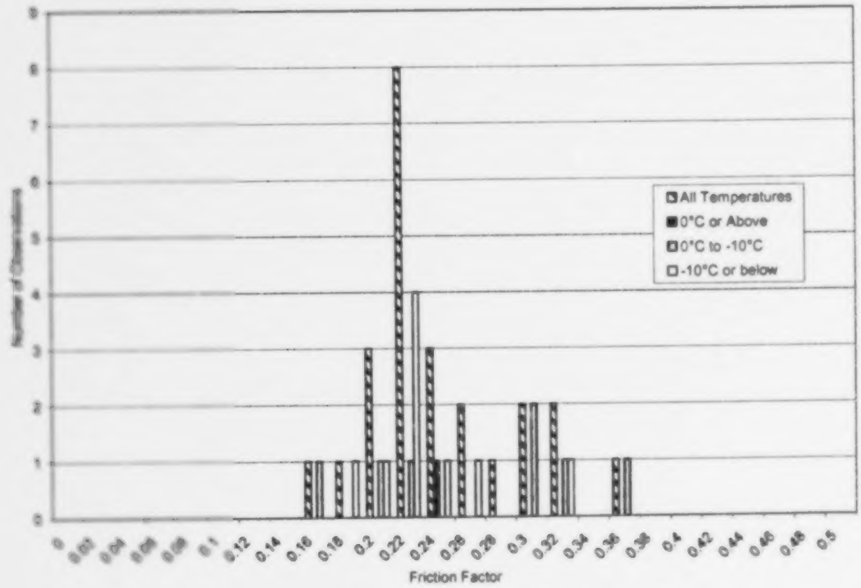
Appendix C.1: Histograms
Appendix C.2: Trend Plots vs. Surface Temperature

APPENDIX C.1

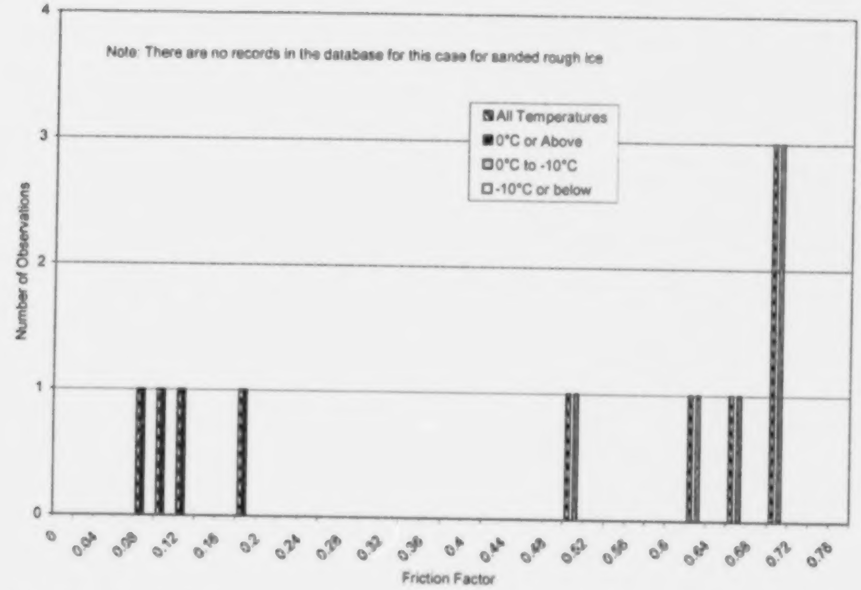
HISTOGRAMS



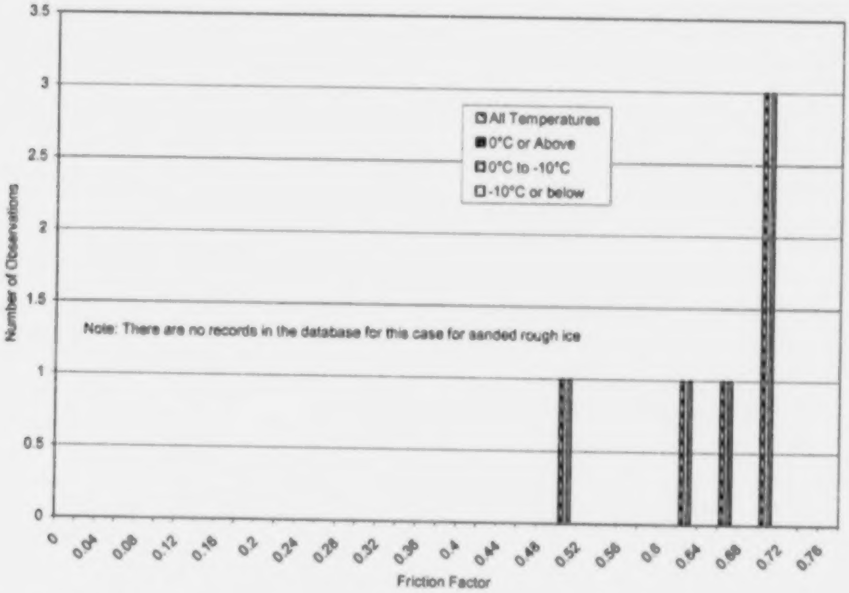
C.1-1: ERD Readings on Bare Sanded Ice: Effect of Temperature



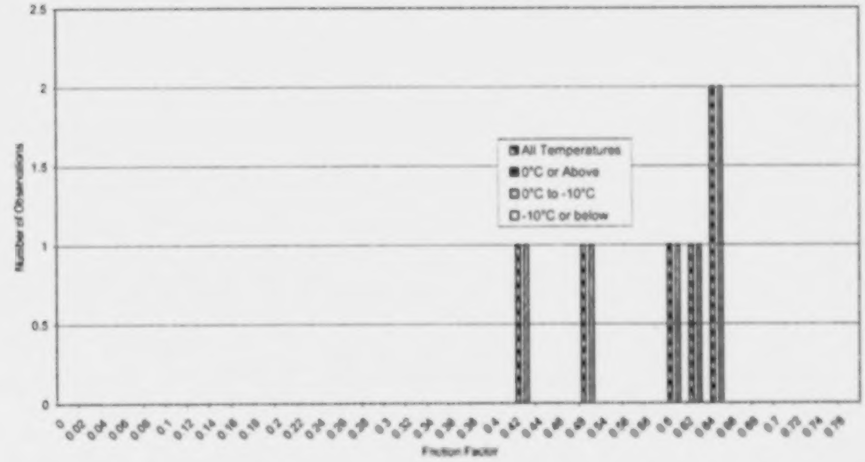
C.1-2: ERD Readings on Sanded Bare Ice and Sanded Rough Ice: Effect of Temperature



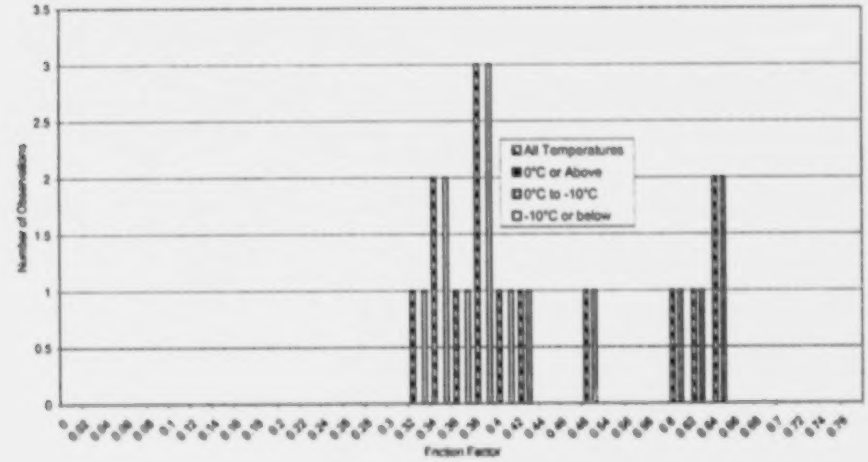
C.1-3: TC SFT'79 (All Configurations) Readings on Bare Sanded Ice: Effect of Temperature



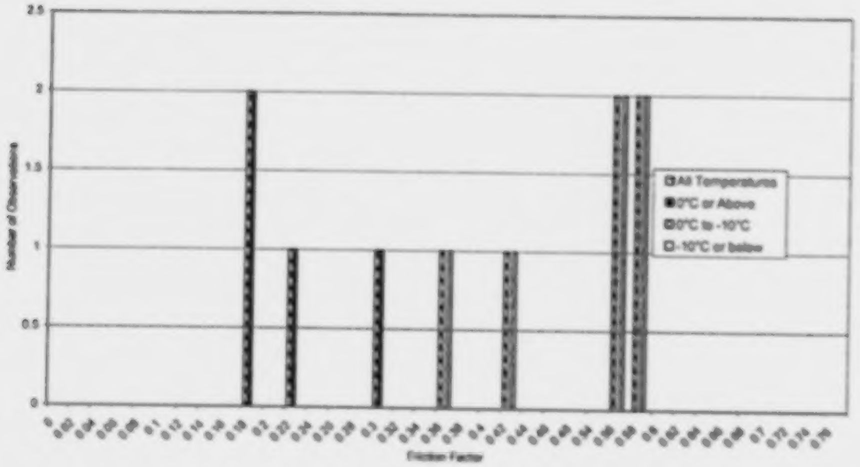
C.1-4: TC SFT'79 (Configuration 3) Readings on Bare Sanded Ice: Effect of Temperature



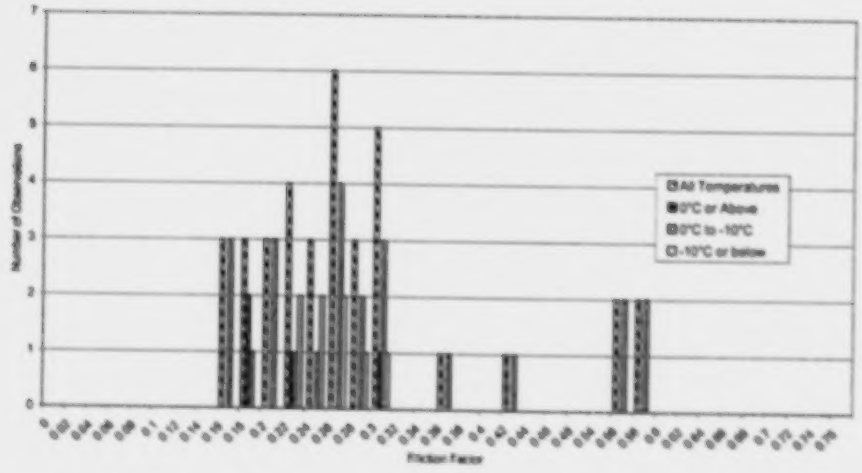
C.1-5: IMAG Force (All Configurations) Readings on Bare Sanded Ice: Effect of Temperature



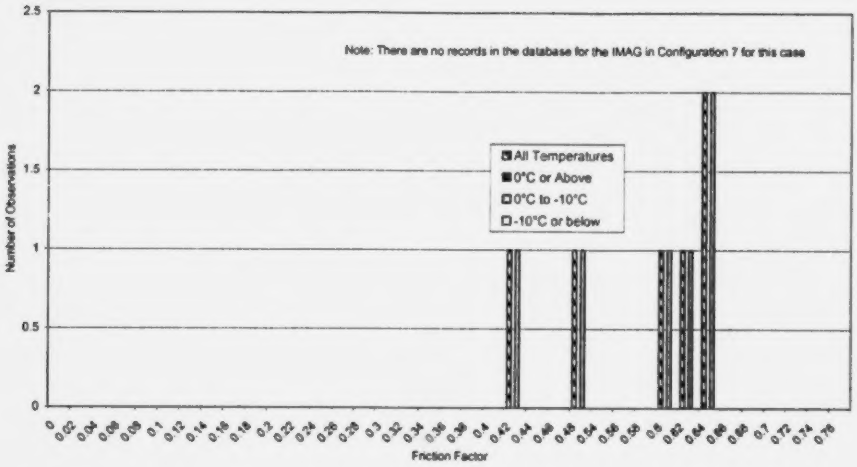
C.1-6: IMAG Force (All Configurations) Readings on Bare Sanded Ice and Rough Ice: Effect of Temperature



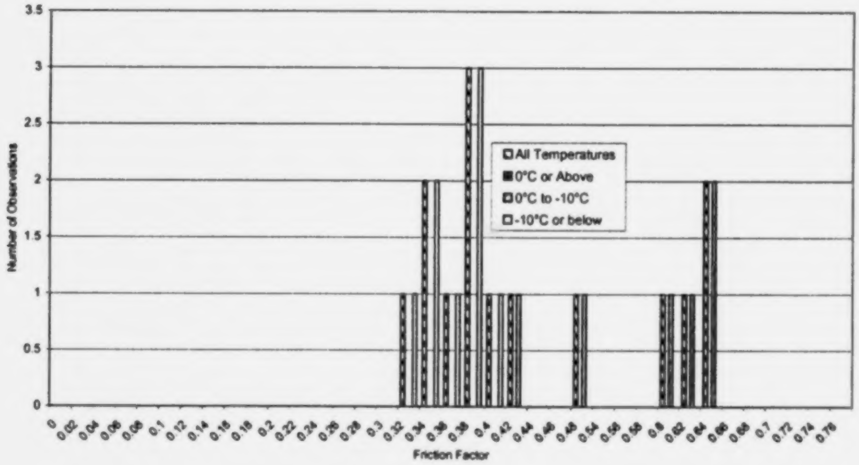
C.1-7: IMAG Torque (All Configurations) Readings on Bare Sanded Ice: Effect of Temperature



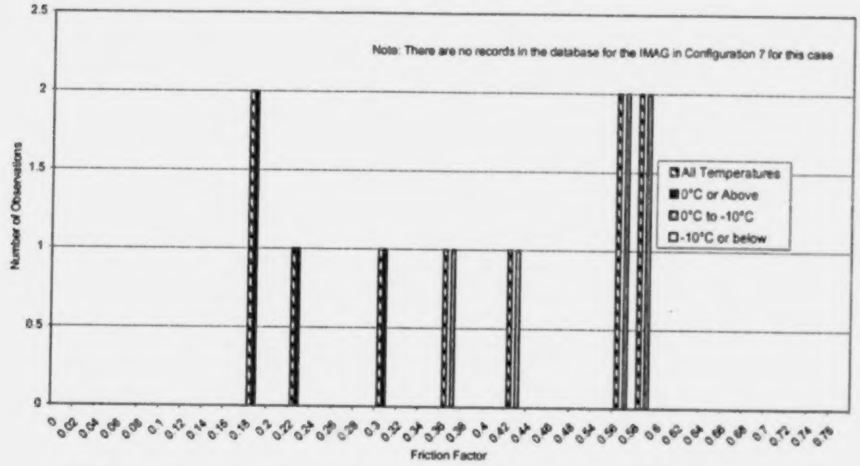
C.1-8: IMAG Torque (All Configurations) Readings on Bare Sanded Ice and Rough Ice: Effect of Temperature



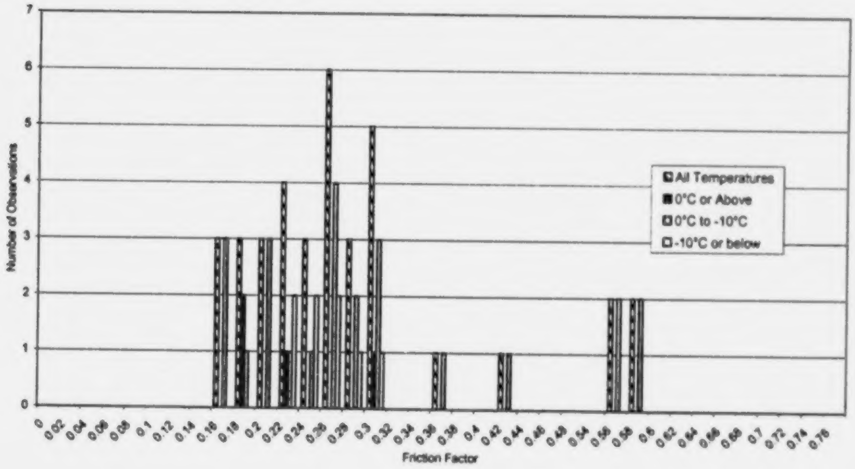
C.1-9: IMAG Force (Configuration 3) Readings on Bare Sanded Ice: Effect of Temperature



C.1-10: IMAG Force (Configuration 3) Readings on Bare Sanded Ice and Rough Ice: Effect of Temperature



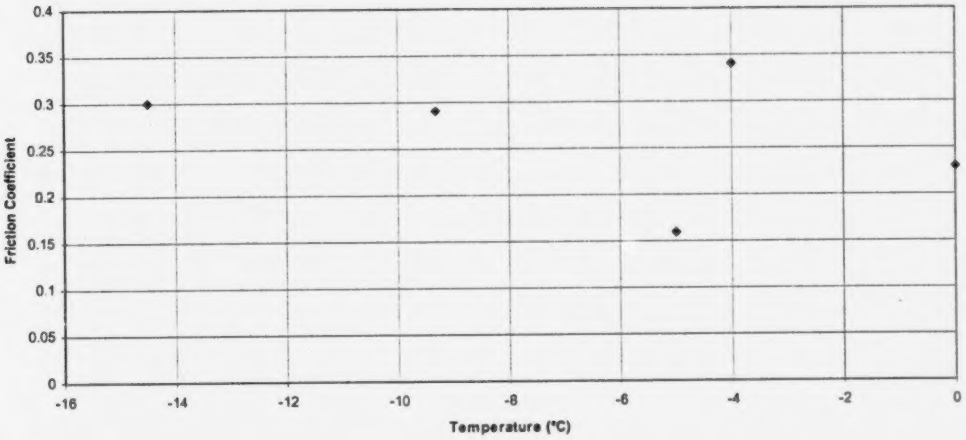
C.1-11: IMAG Torque (Configuration 3) Readings on Bare Sanded Ice: Effect of Temperature



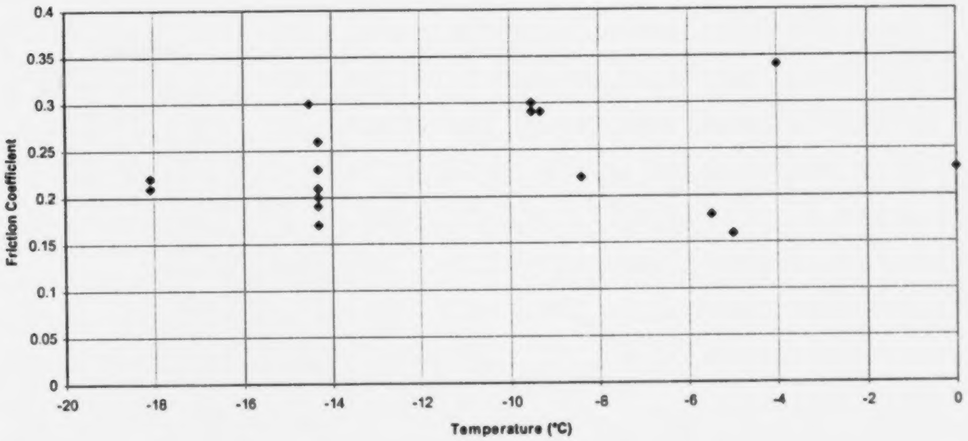
C.1-12: IMAG Torque (Configuration 3) Readings on Bare Sanded Ice and Rough Ice: Effect of Temperature

APPENDIX C.2

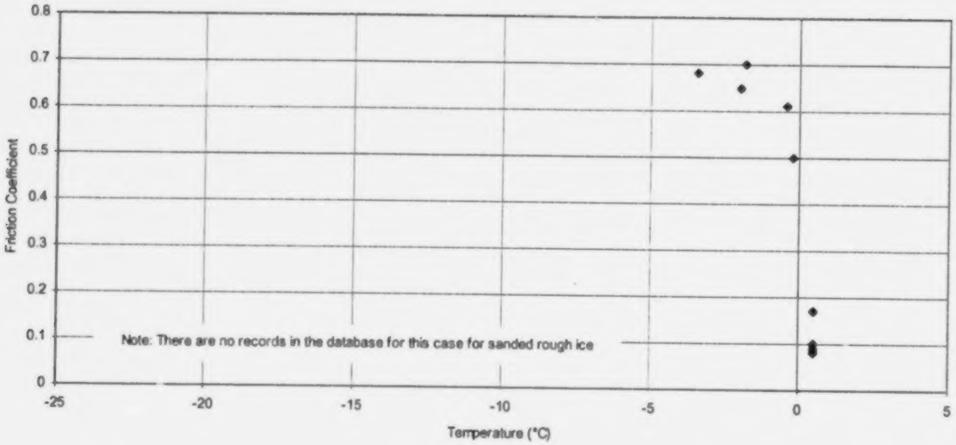
TREND PLOTS VS. SURFACE TEMPERATURE



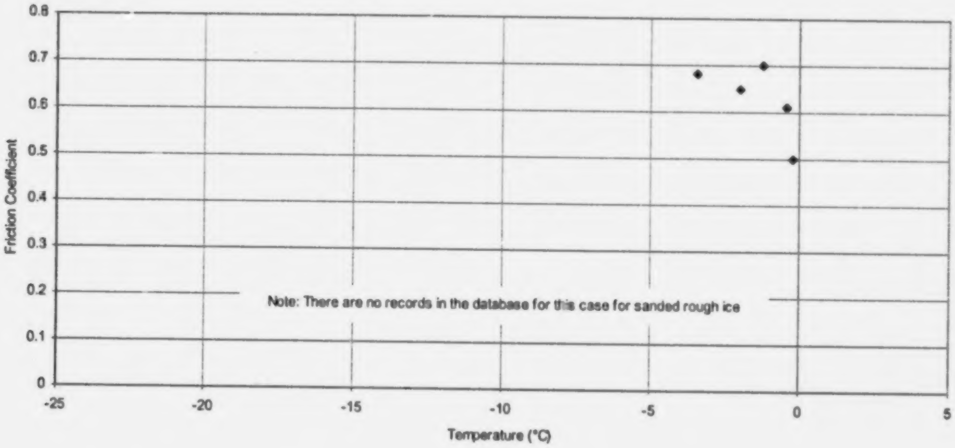
C.2-1: Effect of Temperature: ERD Readings on Bare Sanded Ice



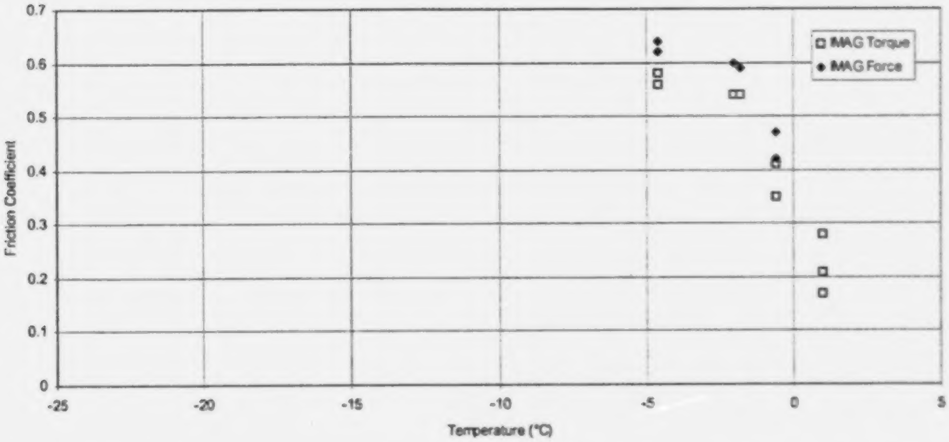
C.2-2: Effect of Temperature: ERD Readings on Bare Sanded Ice and Sanded Rough Ice



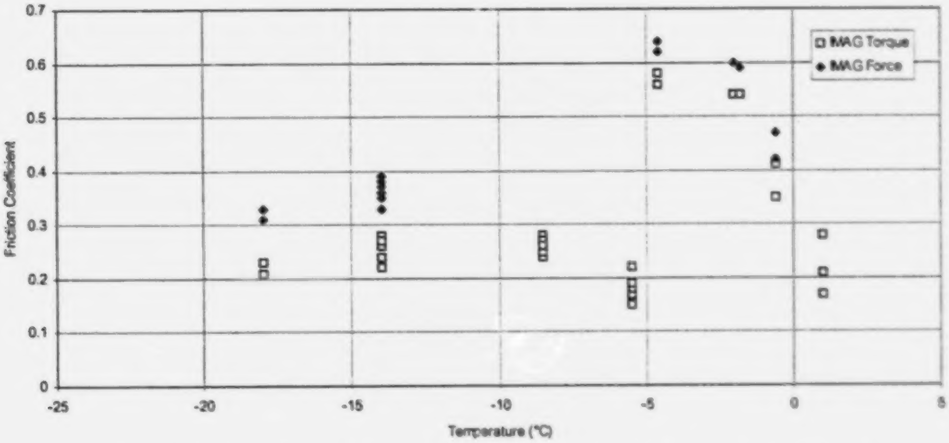
C.2-3: Effect of Temperature: TC SFT'79 (All Configurations) Readings on Bare Sanded Ice



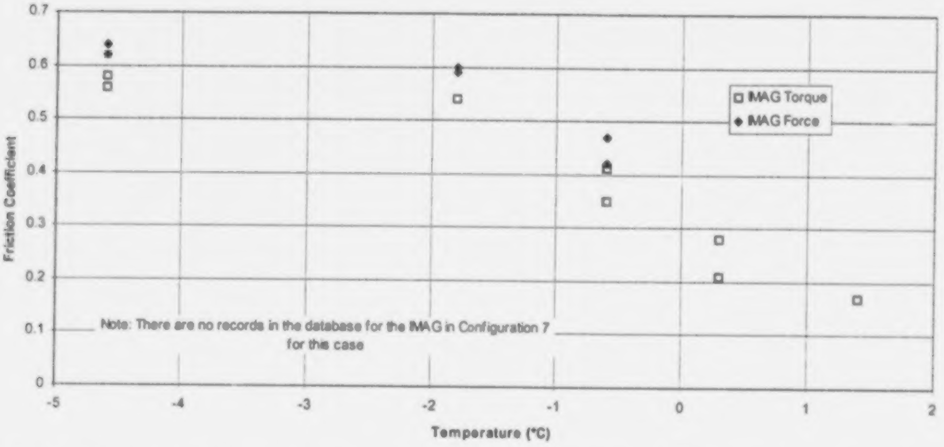
C.2-4: Effect of Temperature: TC SFT'79 (Configuration 3) Readings on Bare Sanded Ice



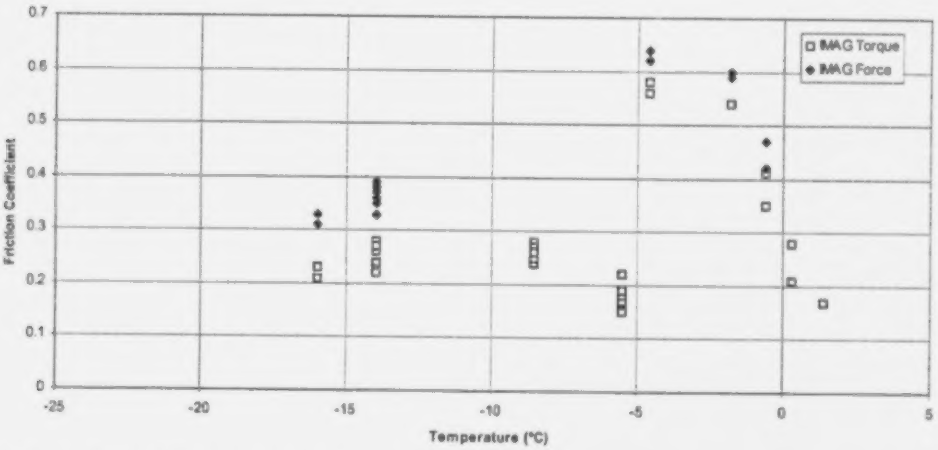
C.2-5: Effect of Temperature: IMAG (All Configurations) Readings on Bare Sanded Ice



C.2-6: Effect of Temperature: IMAG (All Configurations) Readings on Bare Sanded Ice and Rough Ice



C.2-7: Effect of Temperature: IMAG (Configuration 3) Readings on Bare Sanded Ice



C.2-8: Effect of Temperature: IMAG (Configurations 3 and 7) Readings on Bare Sanded Ice and Rough Ice

APPENDIX D

RESULTS FOR SNOW ON PAVEMENT

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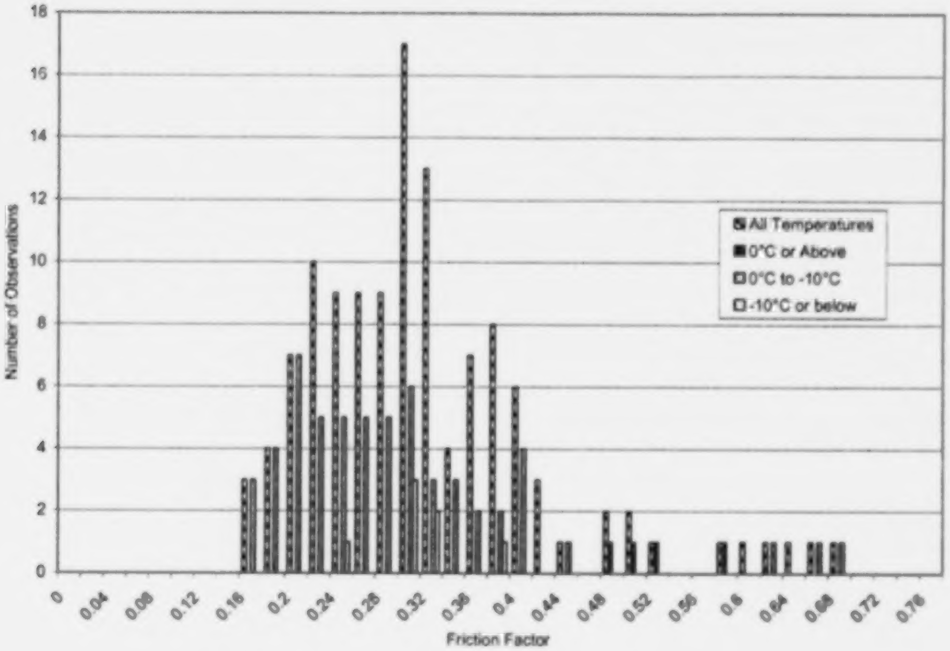
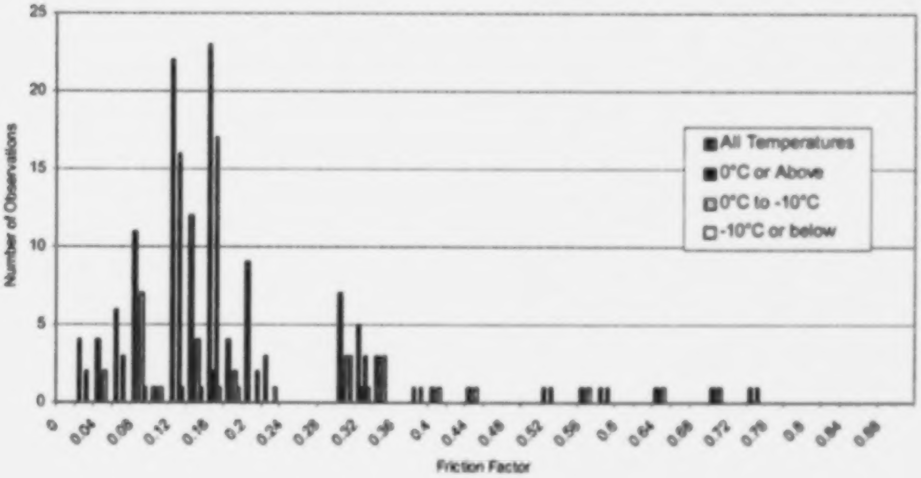
Appendix D.6: Trend Plots vs. Snow Depth (Snow Depths 10 mm or Less)

APPENDIX D.1

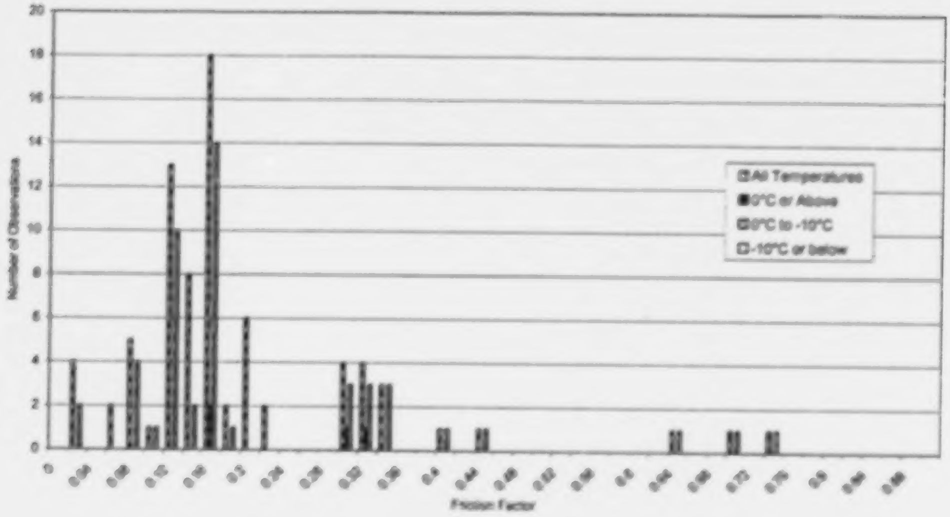
HISTOGRAMS
(ALL SNOW DEPTHS)



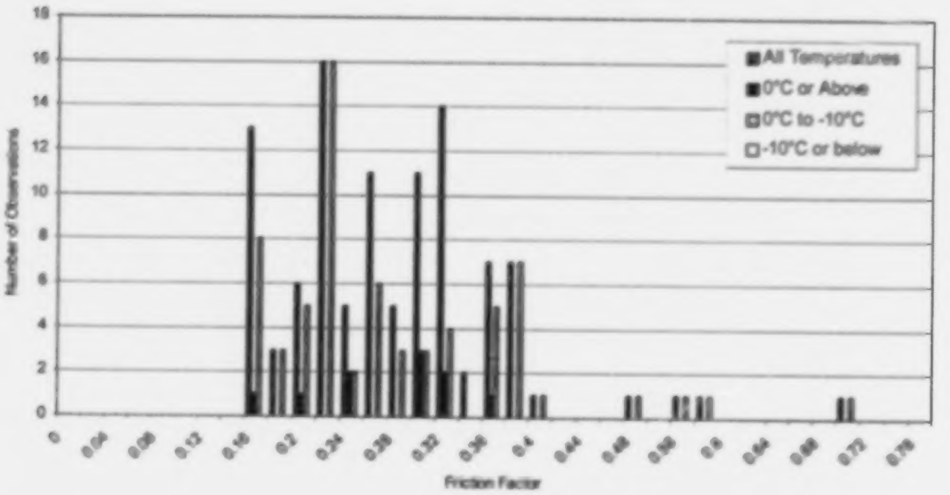
D.1-1: ERD Readings for Snow on Pavement: Effect of Temperature



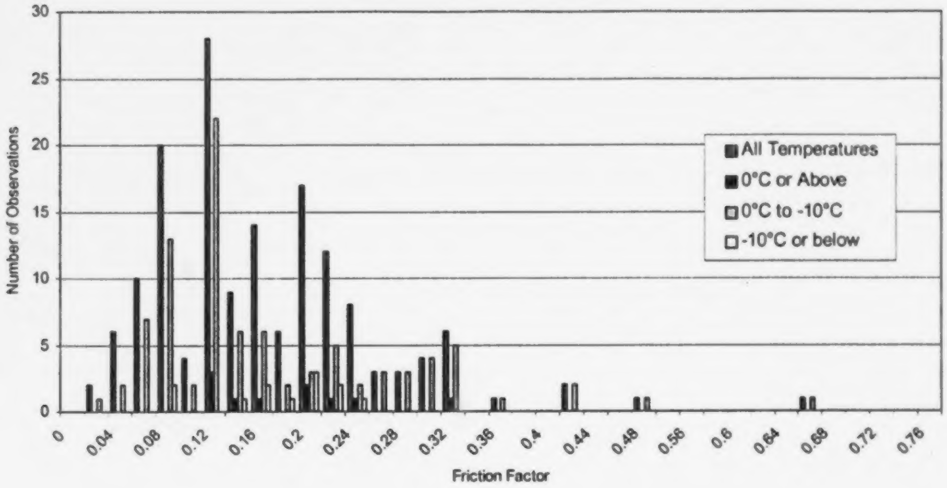
D.1-2: TC SFT'79 (All Configurations) Readings for Snow on Pavement: Effect of Temperature



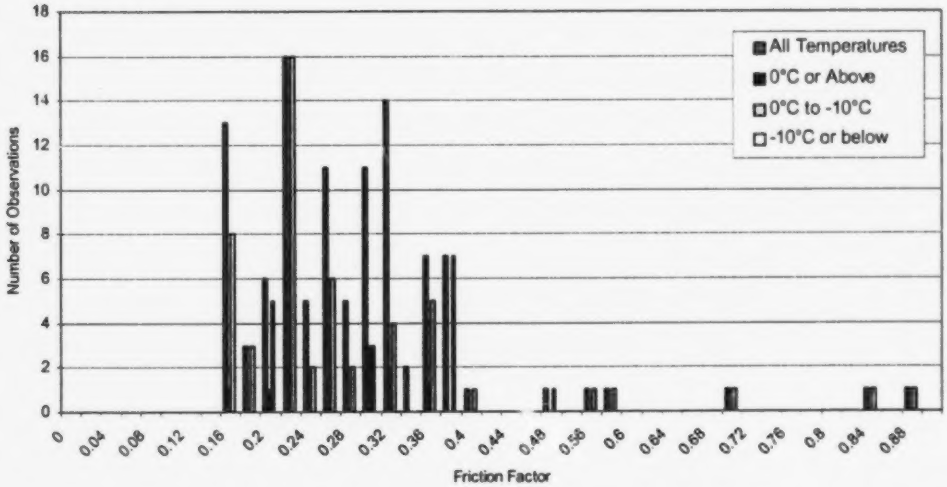
D.1-3: TC SFT'79 (Configuration 3) Readings for Snow on Pavement: Effect of Temperature



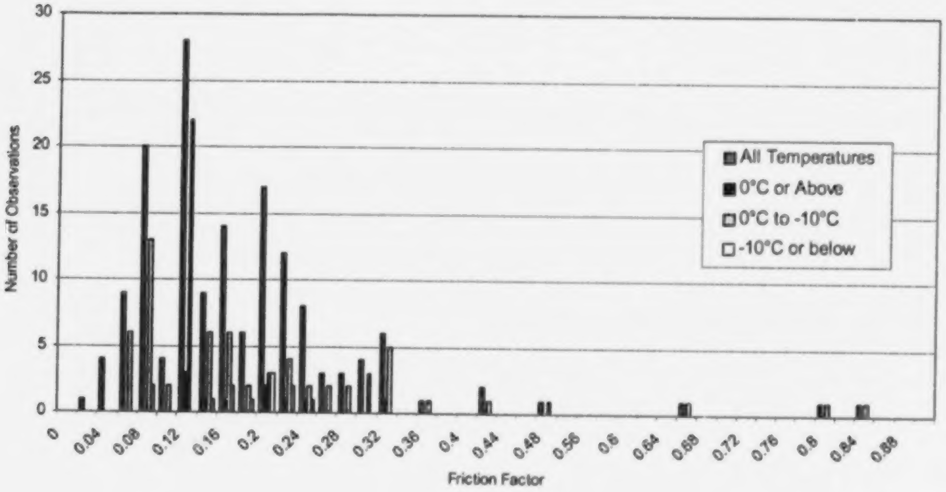
D.1-4: IMAG Force (All Configurations) Readings for Snow on Pavement: Effect of Temperature



D.1-5: IMAG Torque (All Configurations) Readings for Snow on Pavement: Effect of Temperature



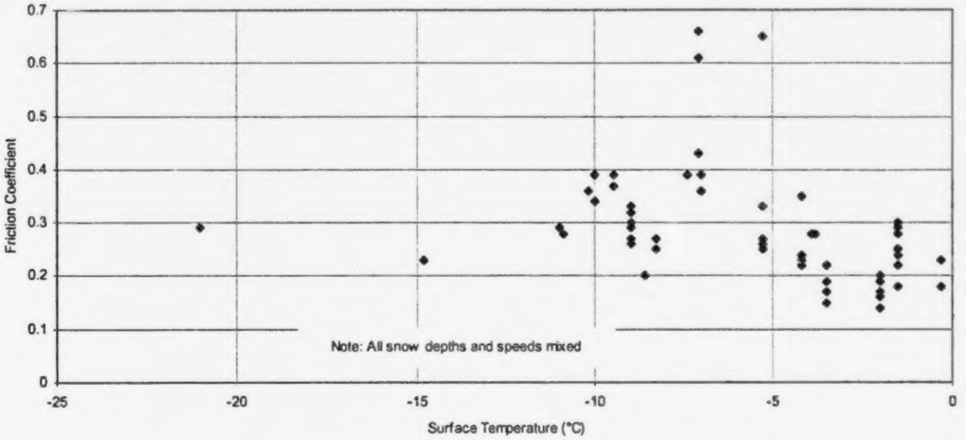
D.1-6: IMAG Force (Configurations 3 and 7) Readings for Snow on Pavement: Effect of Temperature



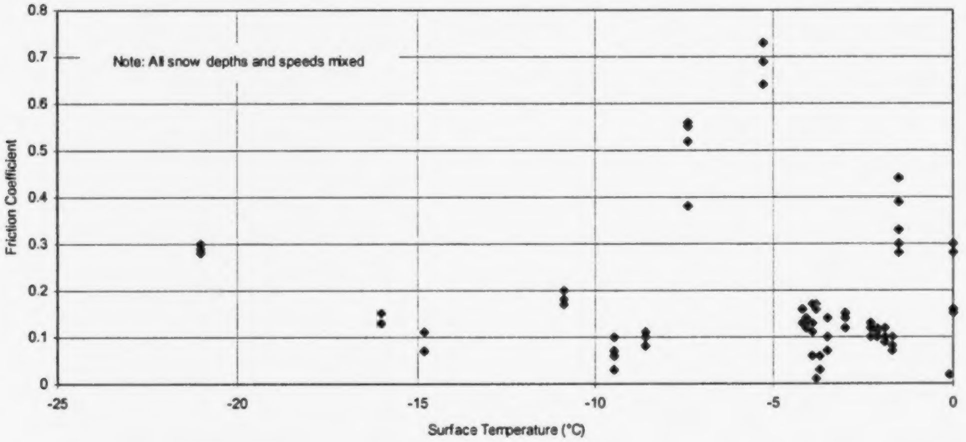
D.1-7: IMAG Torque (Configurations 3 and 7) Readings for Snow on Pavement: Effect of Temperature

APPENDIX D.2

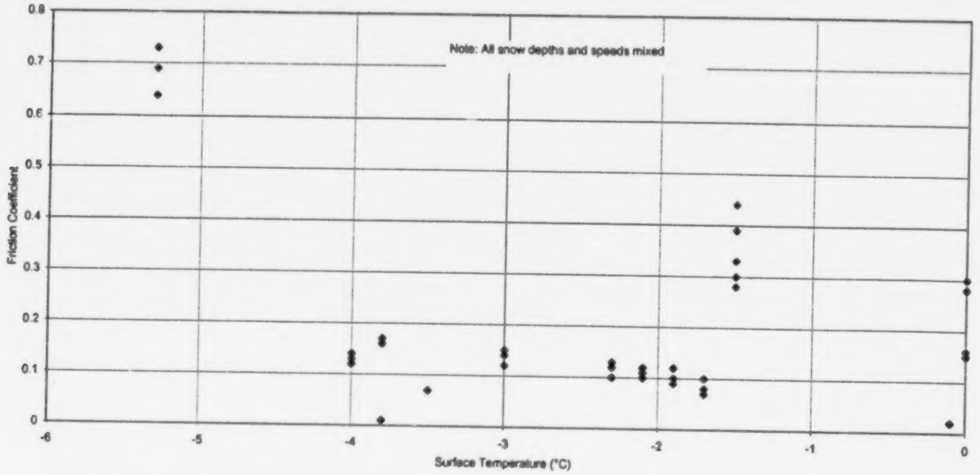
TREND PLOTS VS. SURFACE TEMPERATURE
(ALL SNOW DEPTHS)



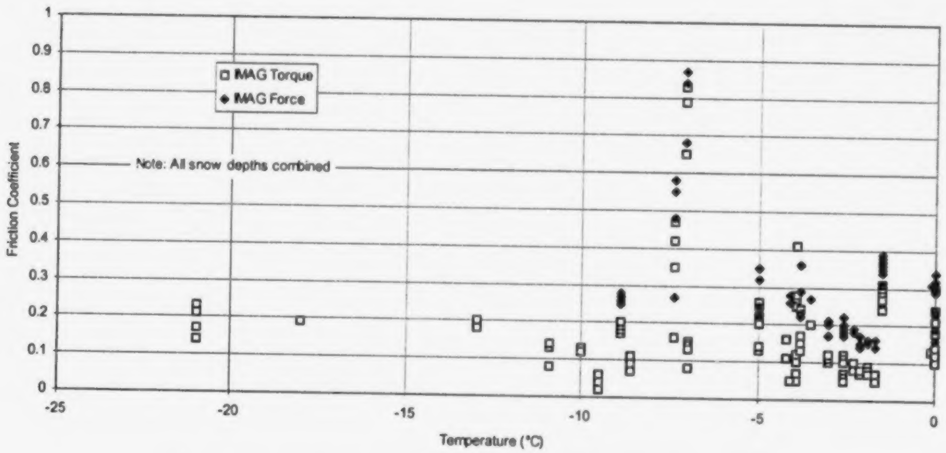
D.2-1: ERD Readings for Snow on Pavement: Effect of Surface Temperature



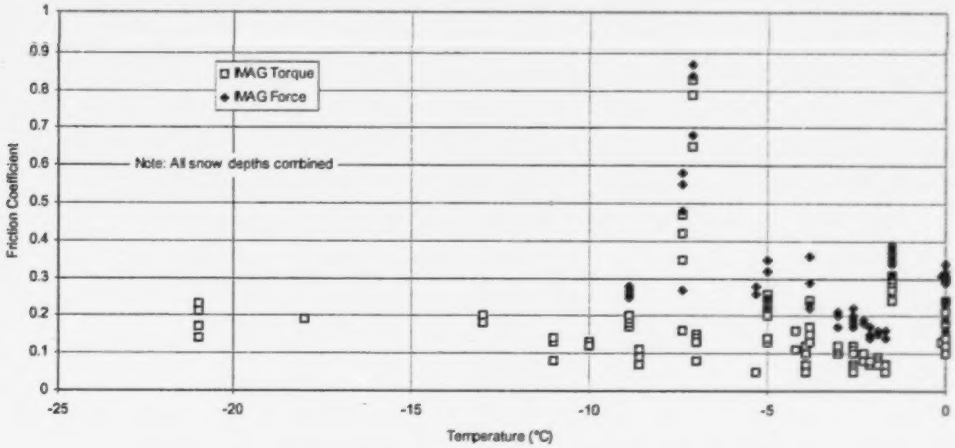
D.2-2: TC SFT'79 (All Configurations) Readings for Snow on Pavement: Effect of Surface Temperature



D.2-3: TC SFT'79 (Configuration 3) Readings for Snow on Pavement: Effect of Surface Temperature



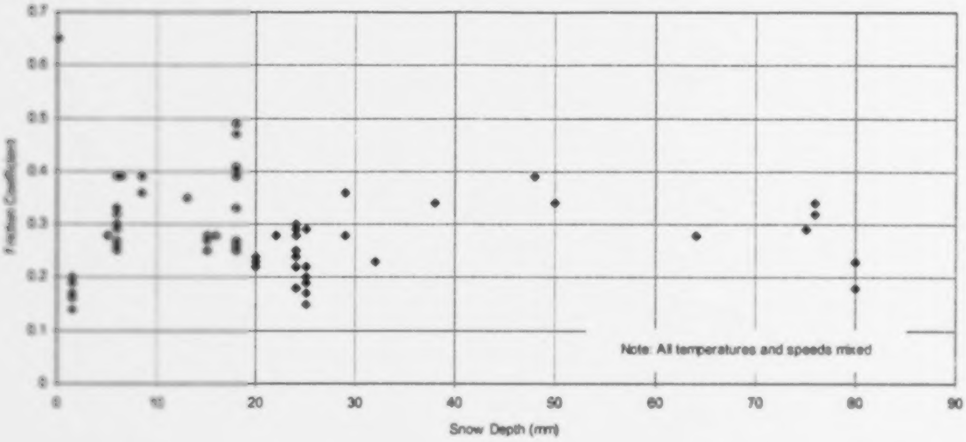
D.2-4: Effects of Temperature: IMAG (All Configurations) Readings for Snow on Pavement



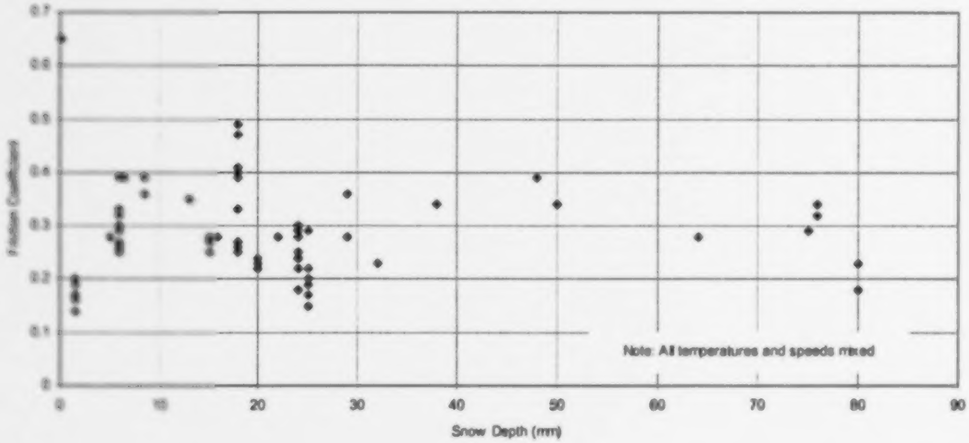
D.2-5: Effect of Temperature: IMAG (Configurations 3 and 7) Readings for Snow on Pavement

APPENDIX D.3

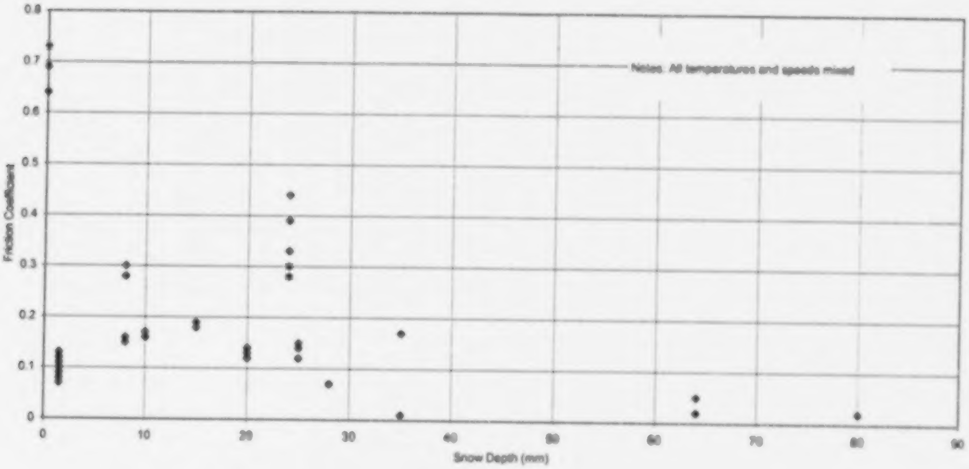
TRENDS PLOTS VS. SNOW DEPTH
(ALL SNOW DEPTHS)



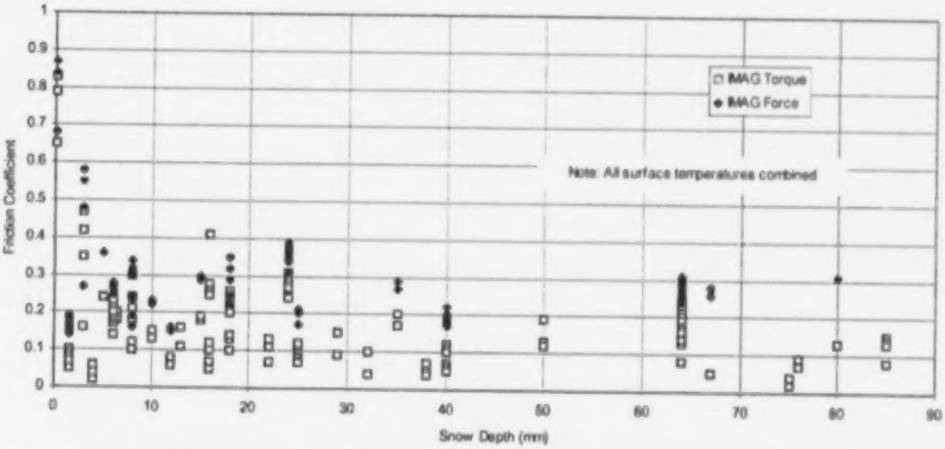
D.3-1: ERD Readings for Snow on Pavement: Effect of Snow Depth



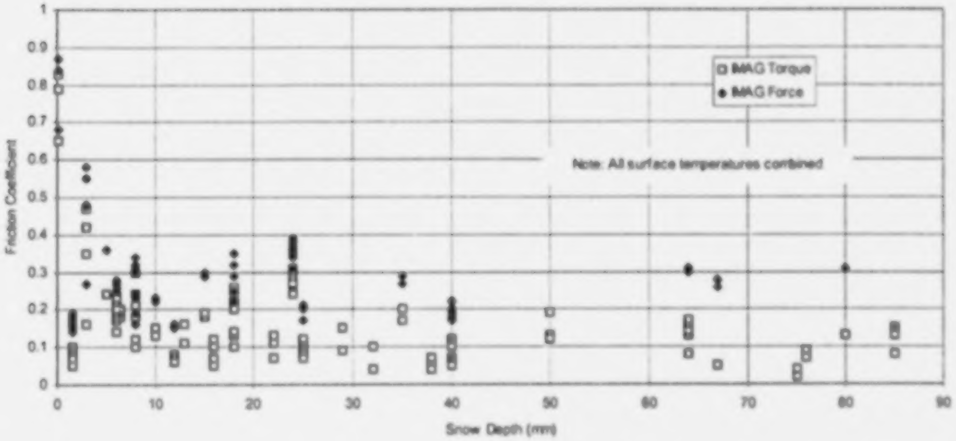
D.3-2: TC SFT'79 (All Configurations) Readings for Snow on Pavement: Effect of Snow Depth



D.3-3: TC SFT'79 (Configuration 3) Readings for Snow on Pavement: Effect of Snow Depth



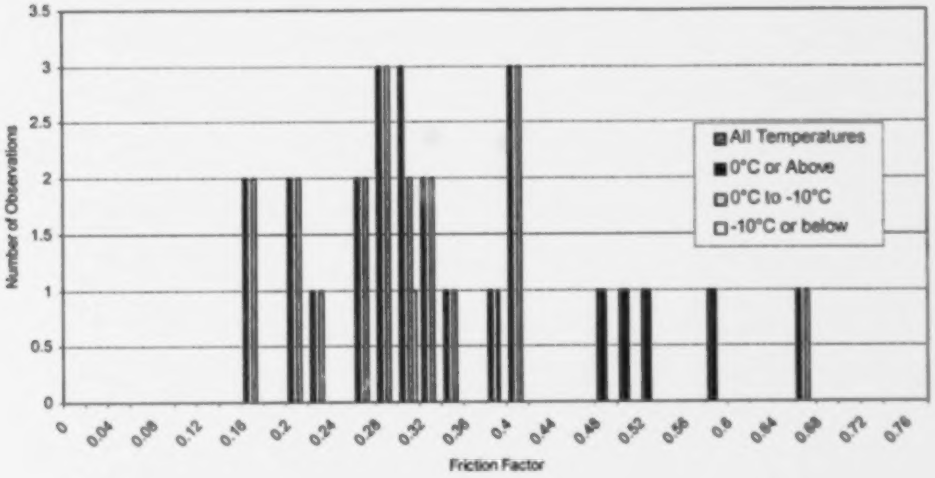
D.3-4: Effect of Snow Depth: IMAG (All Configurations) Readings for Snow on Pavement



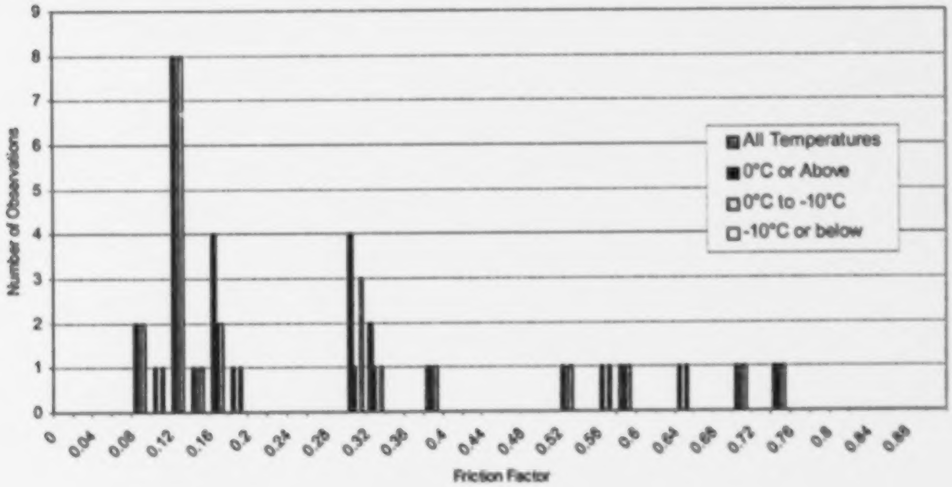
D.3-5: Effect of Snow Depth: IMAG (Configurations 3 and 7) Readings for Snow on Pavement

APPENDIX D.4

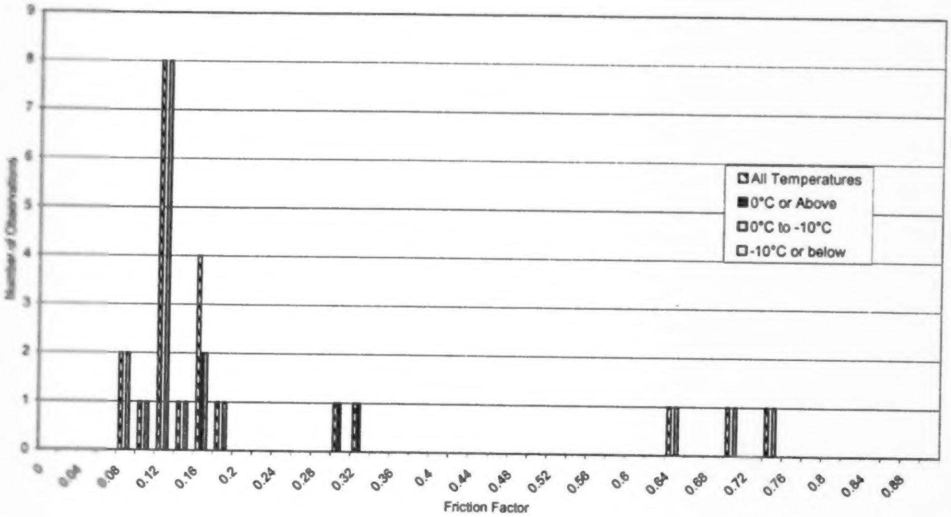
HISTOGRAMS FOR SNOW ON PAVEMENT (SNOW DEPTHS 10 MM OR LESS)



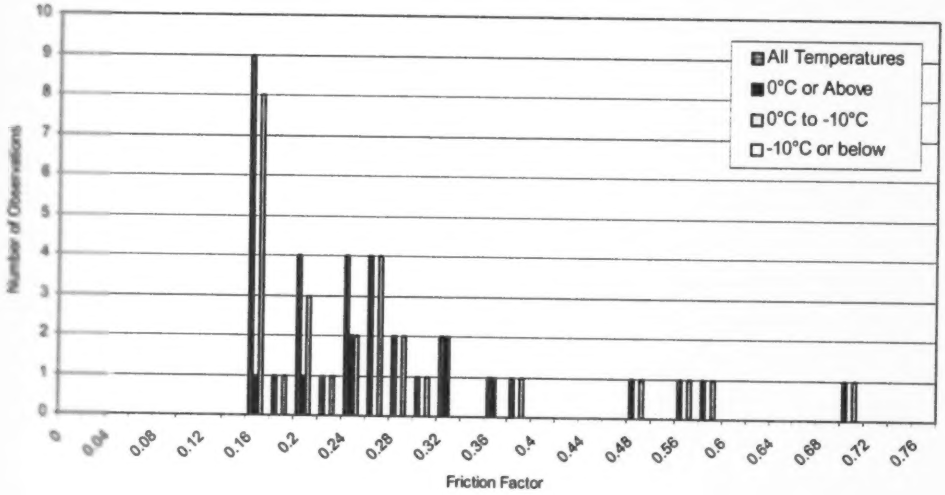
D.4-1: ERD Readings for Snow on Pavement: Effect of Temperature



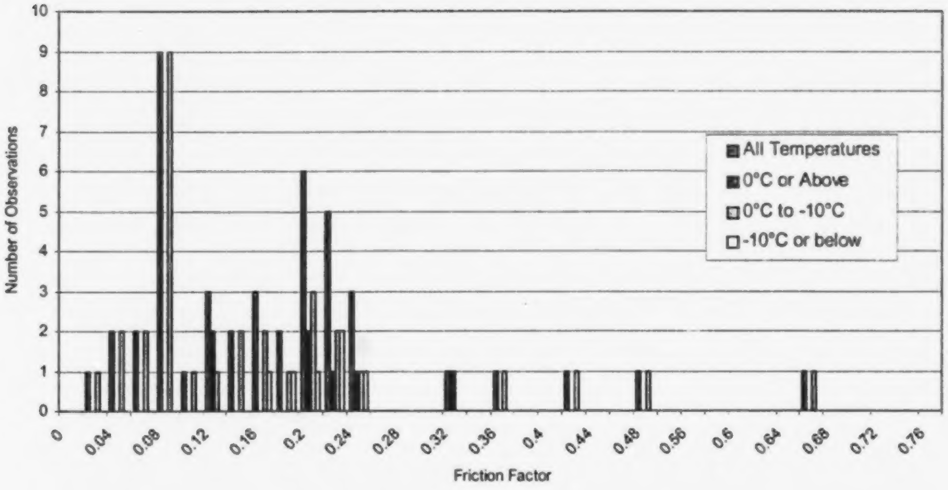
D.4-2: TC SFT'79 (All Configurations) Readings for Snow on Pavement: Effect of Temperature



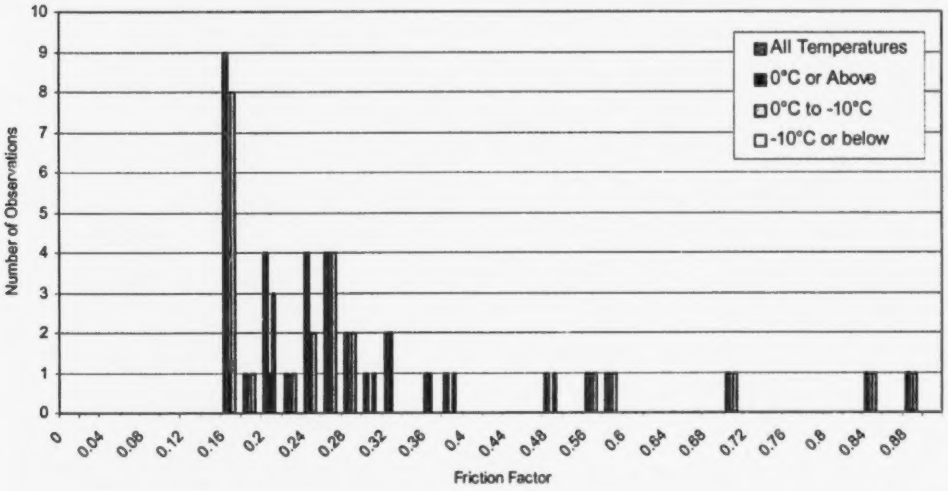
D.4-3: TC SFT'79 (Configuration 3) Readings for Snow on Pavement: Effect of Temperature



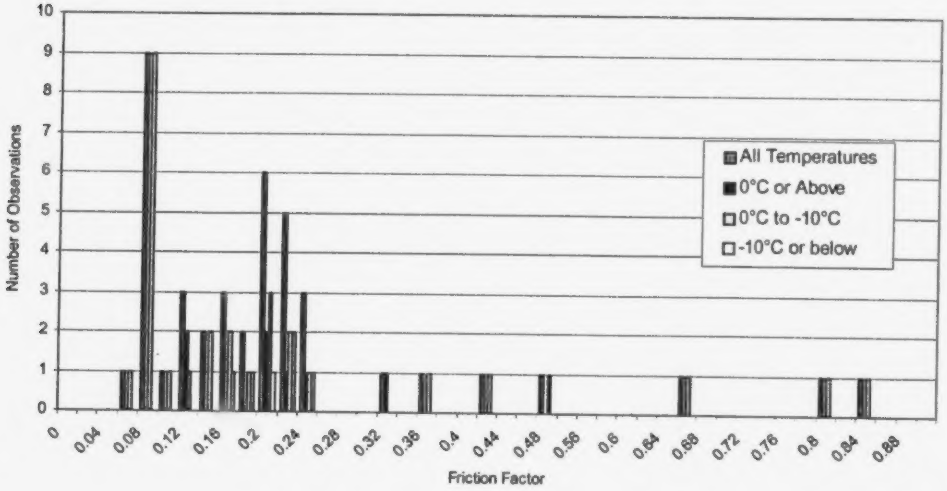
D.4-4: IMAG Force (All Configurations) Readings for Snow on Pavement: Effect of Temperature



D.4-5: IMAG Torque (All Configurations) Readings for Snow on Pavement: Effect of Temperature



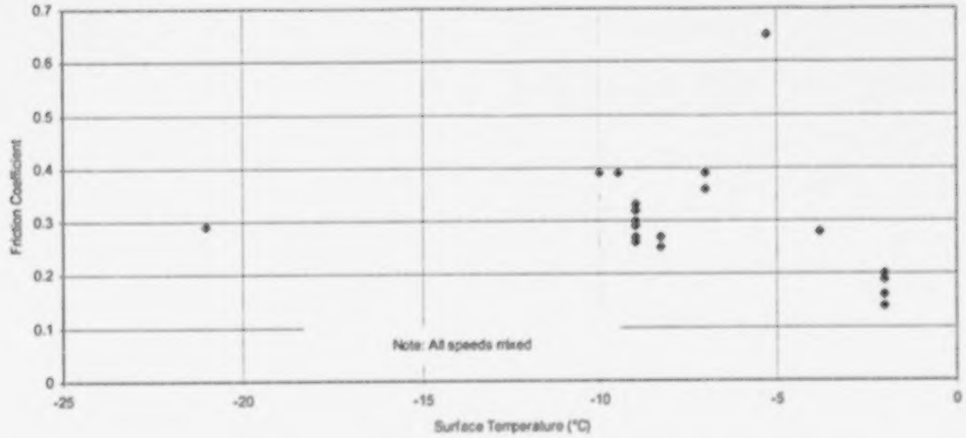
D.4-6: IMAG Force (Configurations 3 and 7) Readings for Snow on Pavement: Effect of Temperature



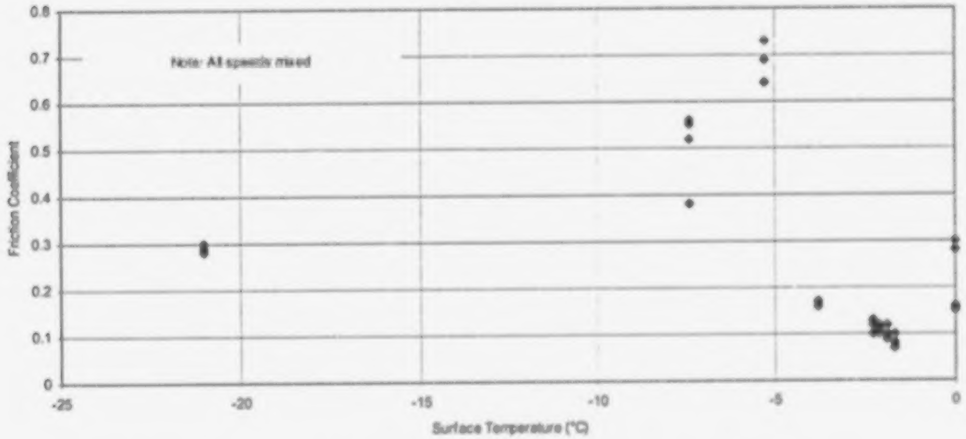
D.4-7: IMAG Torque (Configurations 3 and 7) Readings for Snow on Pavement: Effect of Temperature

APPENDIX D.5

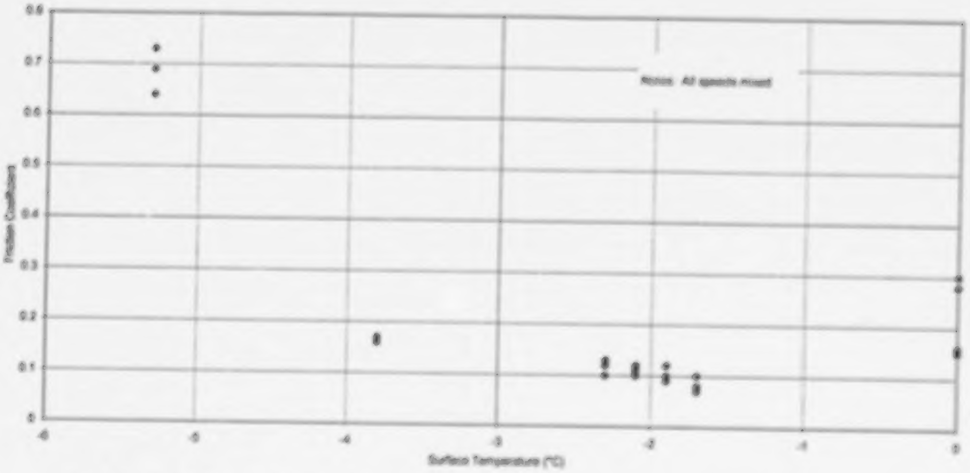
TRENDPLOTS VS. SURFACE TEMPERATURE
(SNOW DEPTHS 10 MM OR LESS)



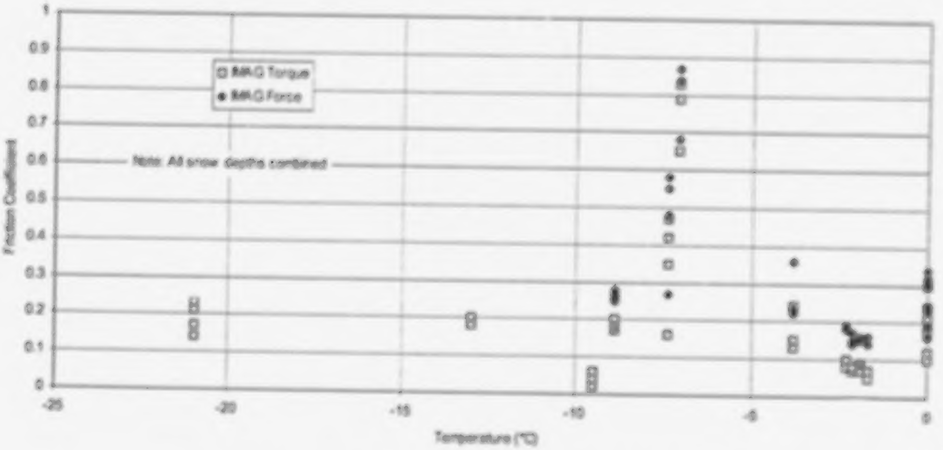
D.5-1: ERD Readings for Snow on Pavement: Effect of Surface Temperature



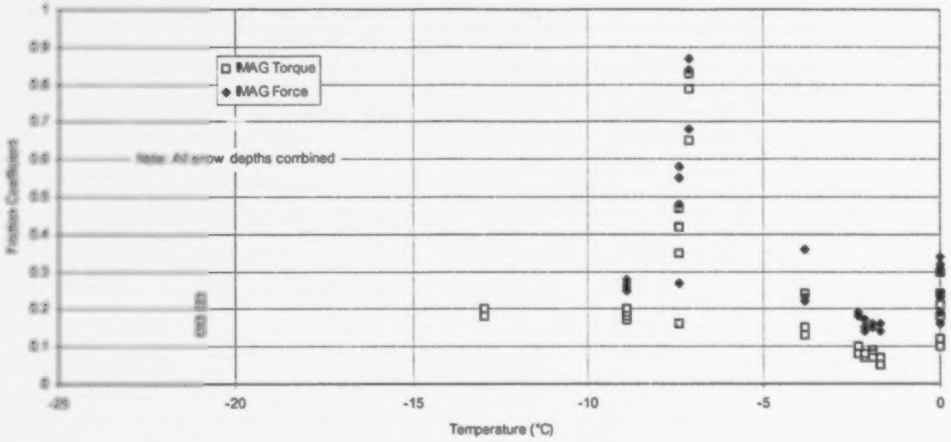
D.5-2: TC SFT'79 (All Configurations) Readings for Snow on Pavement: Effect of Surface Temperature



D.5-3: TC SFT'79 (Configuration 3) Readings for Snow on Pavement: Effect of Surface Temperature



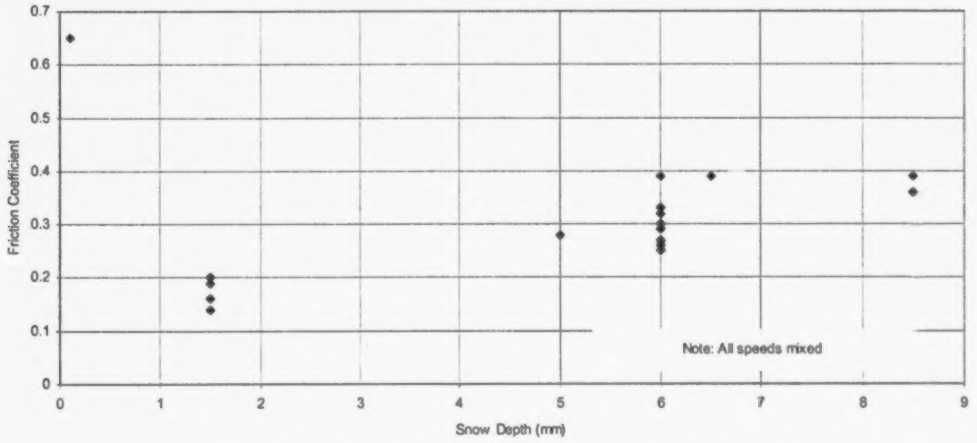
D.5-4: Effect of Temperature: IMAG (All Configurations) Readings for Snow on Pavement



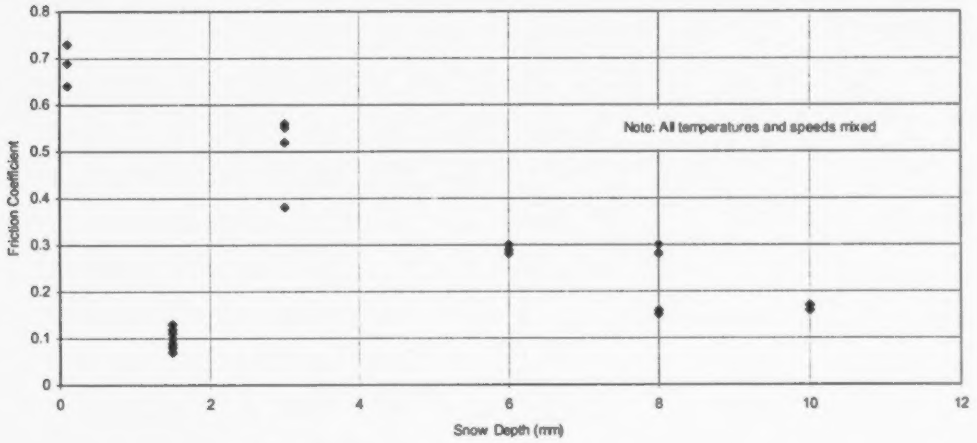
D.5-5: Effect of Temperature: IMAG (Configurations 3 and 7) Readings for Snow on Pavement

APPENDIX D.6

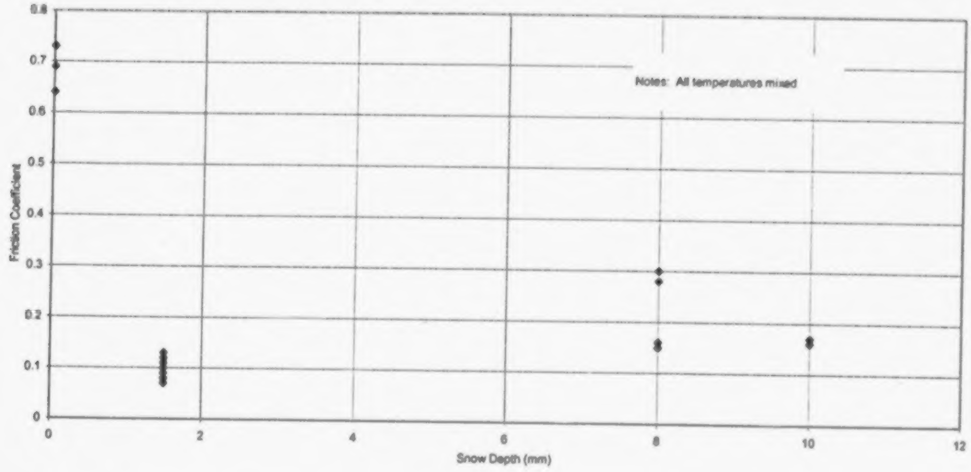
TREND PLOTS VS. SNOW DEPTH
(SNOW DEPTHS 10 MM OR LESS)



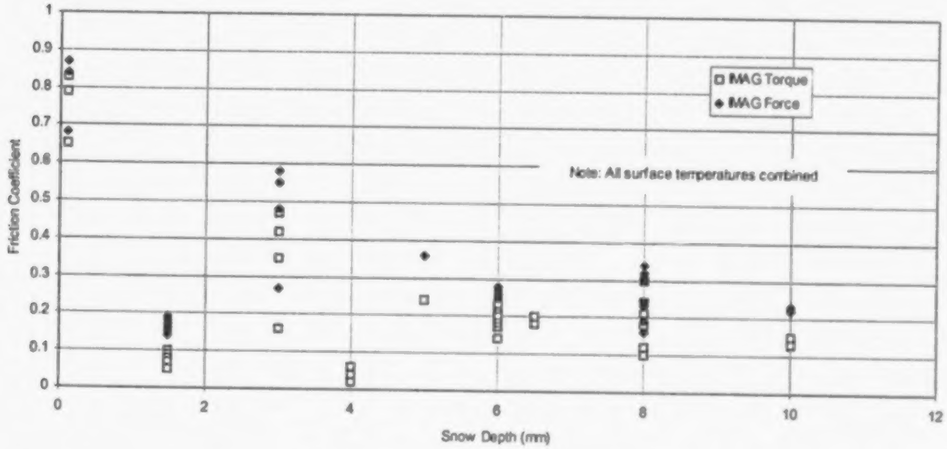
D.6-1: ERD Readings for Snow on Pavement: Effect of Snow Depth



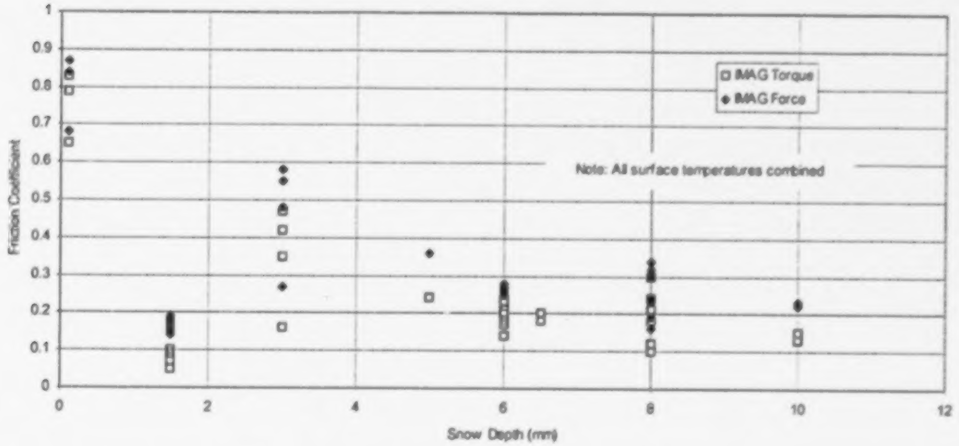
D.6-2: TC SFT'79 (All Configurations) Readings for Snow on Pavement: Effect of Snow Depth



D.6-3: TC SFT'79 (Configuration 3) Readings for Snow on Pavement: Effect of Snow Depth



D.6-4: Effect of Snow Depth: IMAG (All Configurations) Readings for Snow on Pavement



D.6-5: Effect of Snow Depth: IMAG (Configurations 3 and 7) Readings for Snow on Pavement

APPENDIX E

RESULTS FOR SNOW ON ICE

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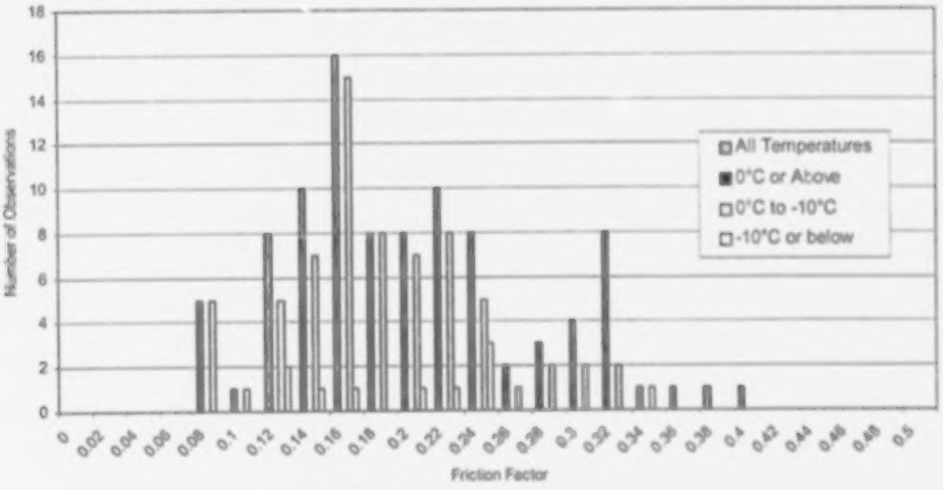
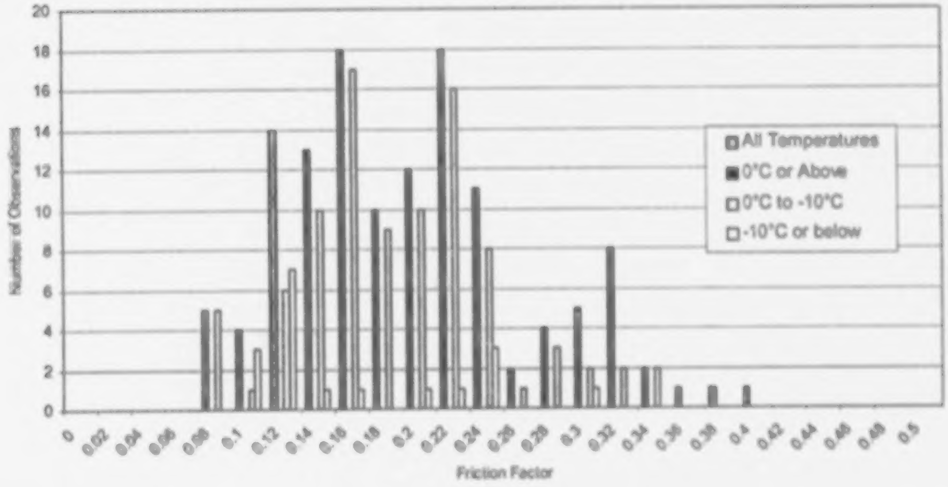
Appendix E.6: Trend Plots vs. Snow Depth (Snow Depths 10 mm or Less)

APPENDIX E.1

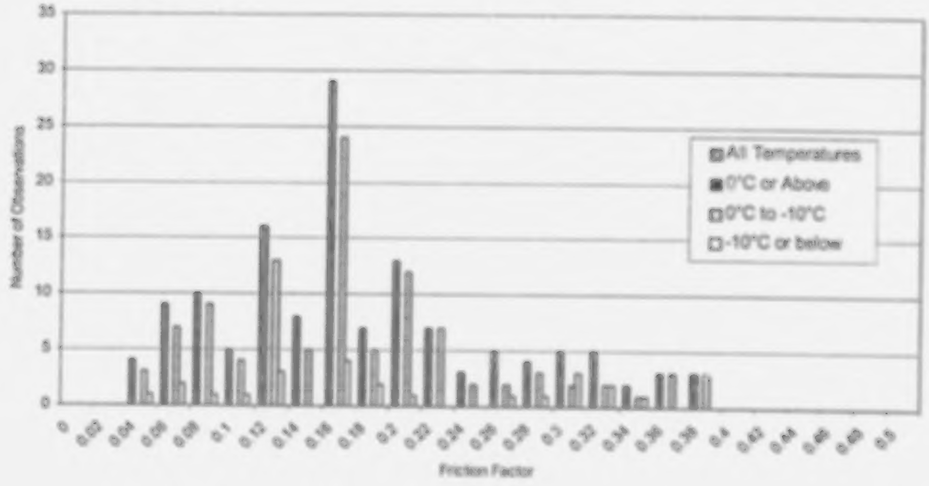
HISTOGRAMS
(ALL SNOW DEPTHS)



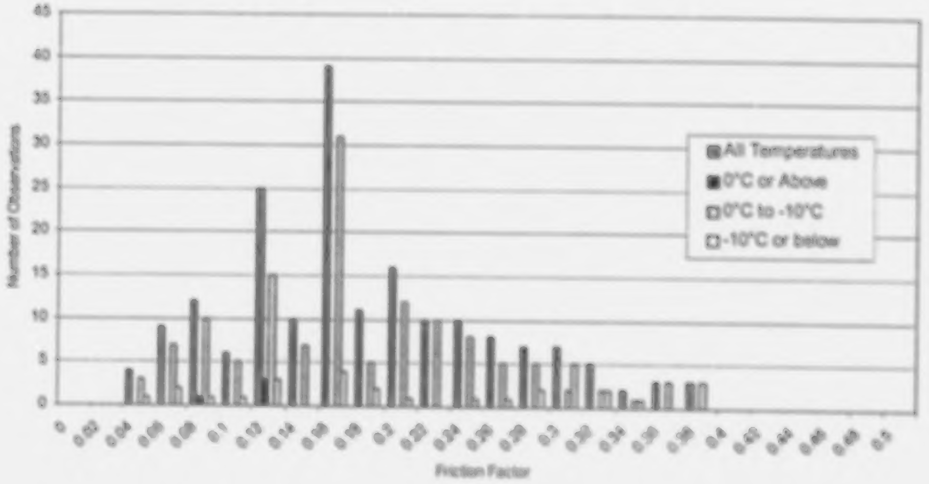
E.1-1: ERD Readings for Snow on an Ice Base: Effect of Temperature



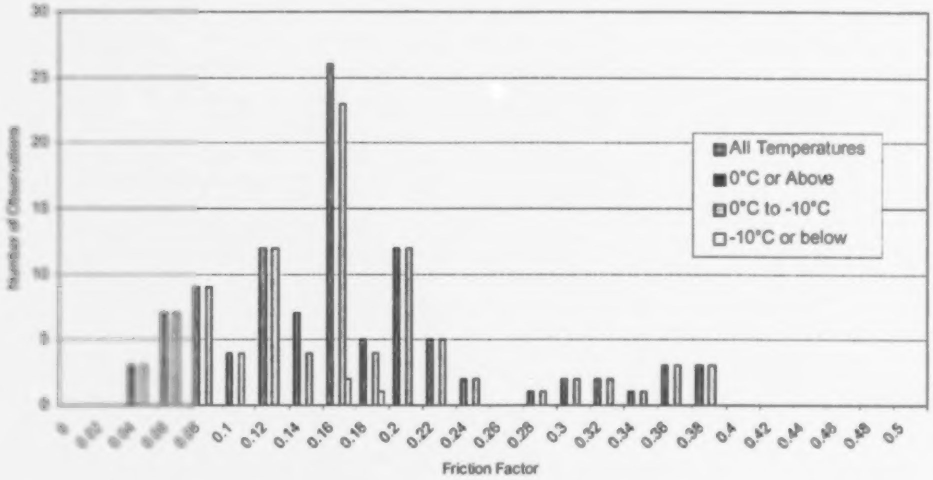
E.1-2: ERD Readings for Snow on Ice Including Rough Ice: Effect of Temperature



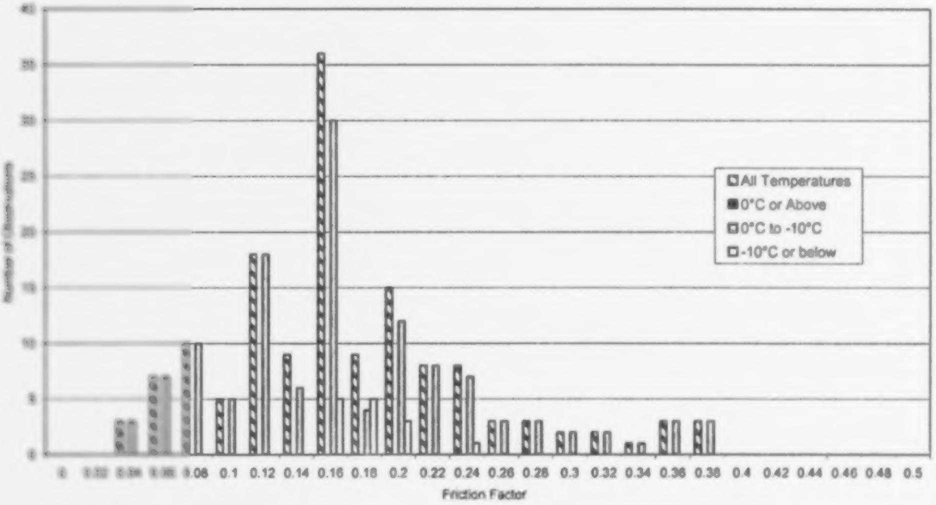
E.1-3: TC SFT'79 (All Configurations) Readings for Snow on an Ice Base: Effect of Temperature



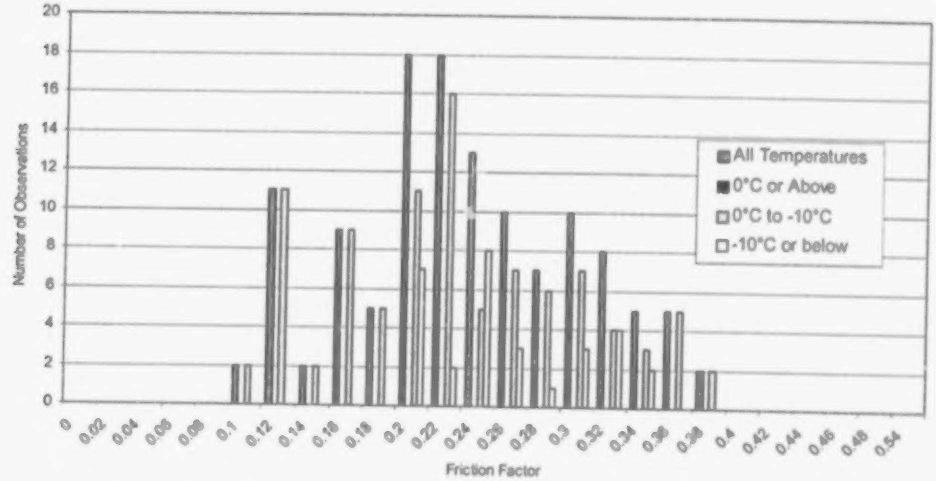
E.1-4: TC SFT'79 (All Configurations) Readings for Snow on Ice Including Rough Ice: Effect of Temperature



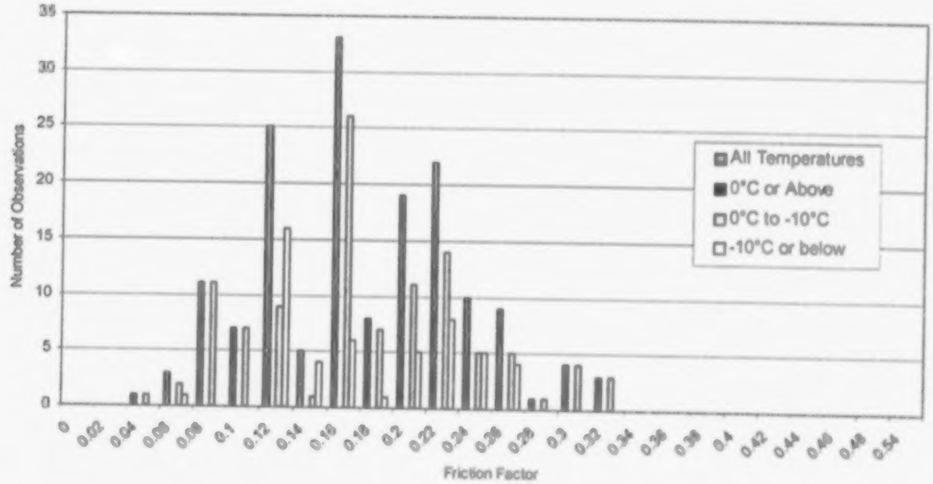
E.1-5: TC SFT'79 (Configuration 3) Readings for Snow on an Ice Base: Effect of Temperature



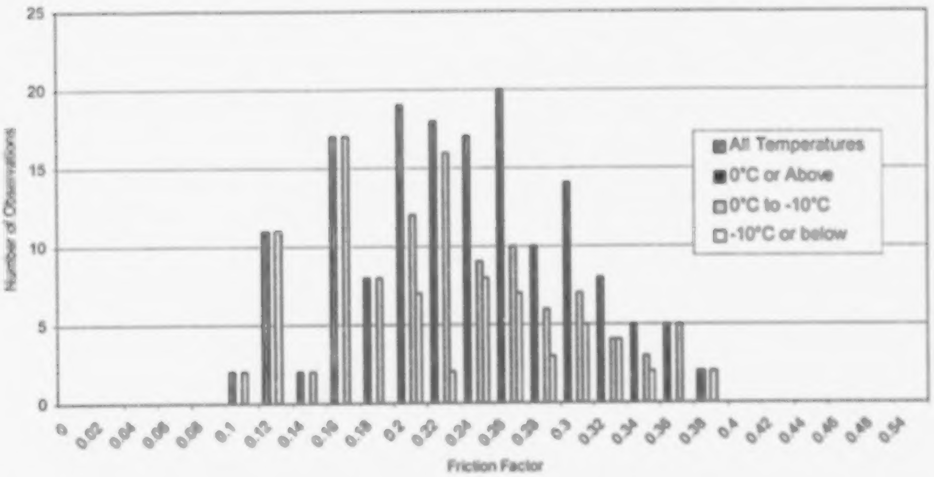
E.1-6: TC SFT'79 (Configuration 3) Readings for Snow on Ice Including Rough Ice: Effect of Temperature



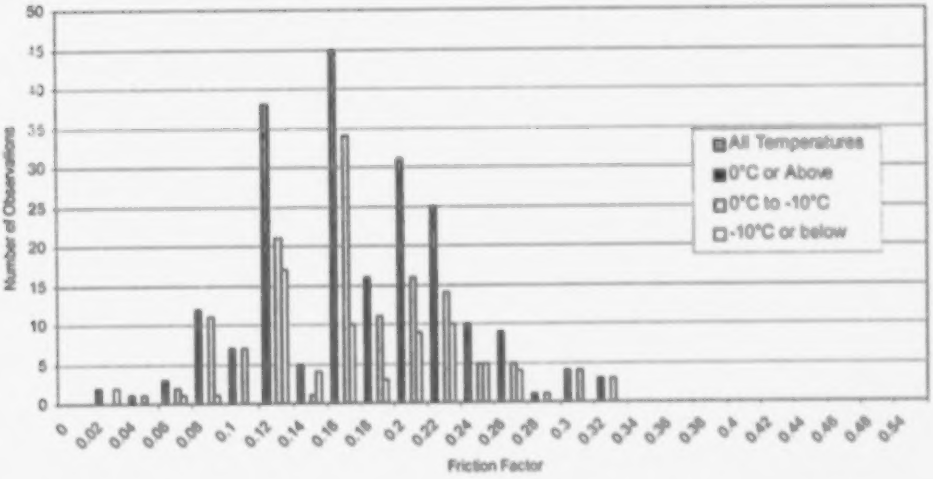
E.1-7: IMAG Force (All Configurations) Readings for Snow on Bare Ice: Effect of Temperature



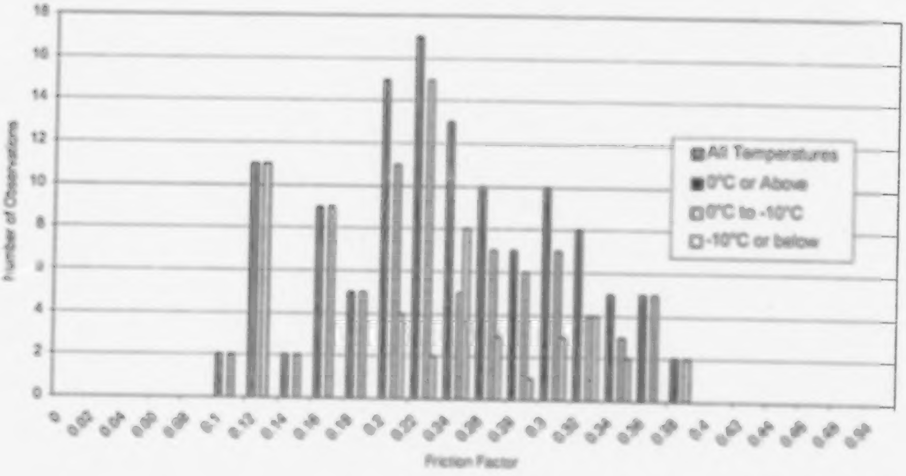
E.1-8: IMAG Torque (All Configurations) Readings for Snow on Bare Ice: Effect of Temperature



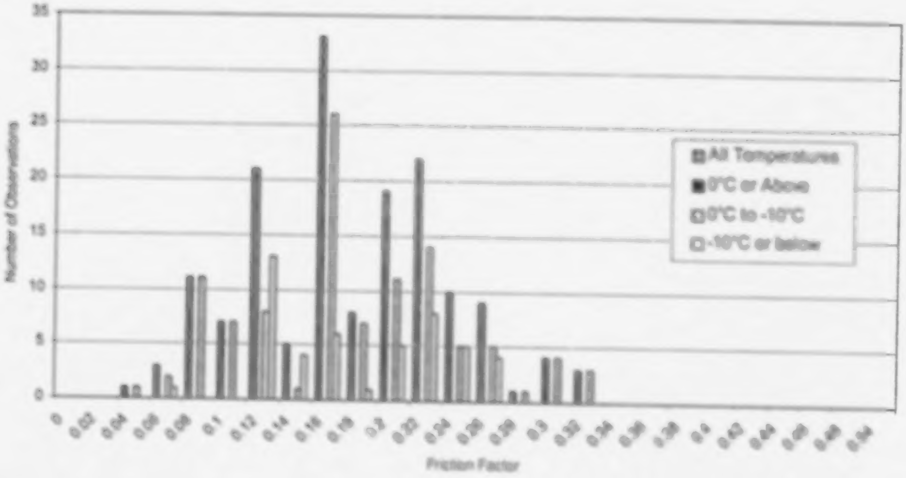
E.1-9: IMAG Force (All Configurations) Readings for Snow on Ice Including Rough Ice: Effect of Temperature



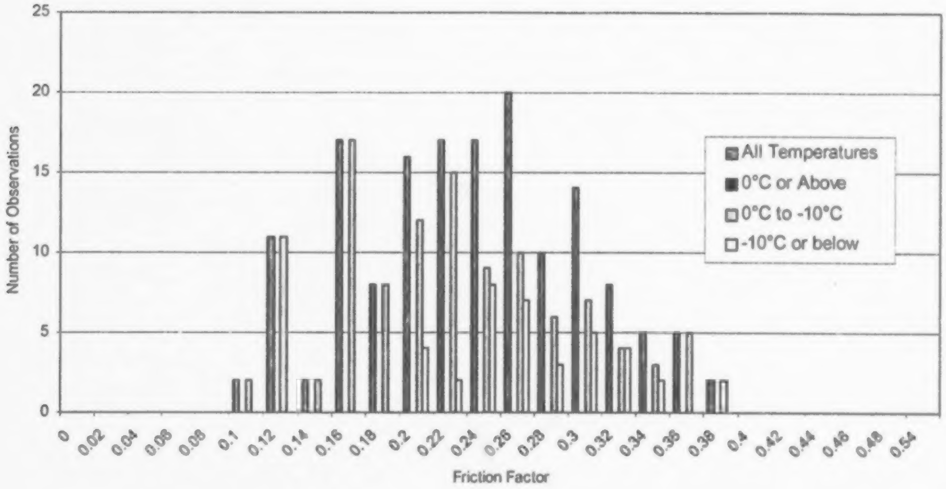
E.1-10: IMAG Torque (All Configurations) Readings for Snow on Ice Including Rough Ice: Effect of Temperature



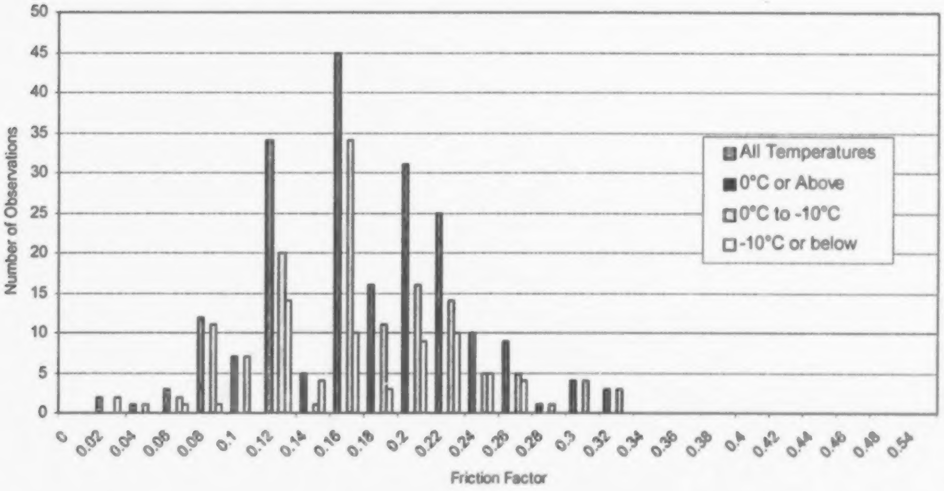
E.1-11: IMAG Force (Configurations 3 and 7) Readings for Snow on Bare Ice: Effect of Temperature



E.1-12: IMAG Torque (Configurations 3 and 7) Readings for Snow on Bare Ice: Effect of Temperature



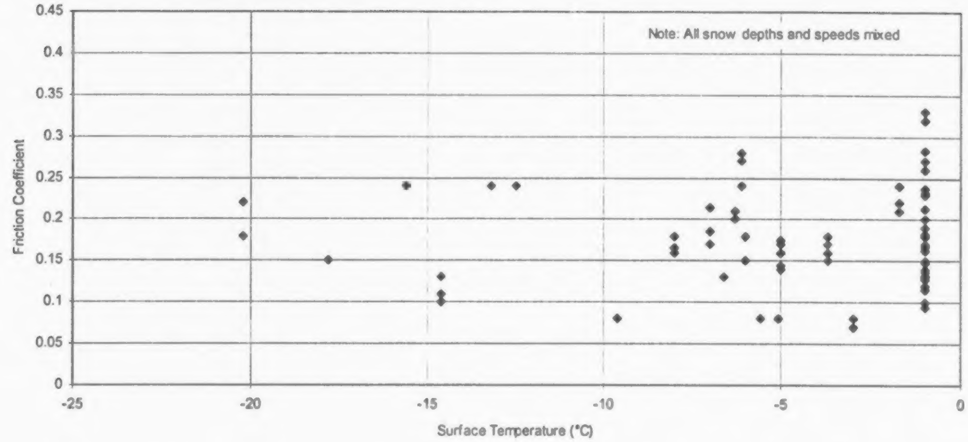
E.1-13: IMAG Force (Configurations 3 and 7) Readings for Snow on Ice Including Rough Ice: Effect of Temperature



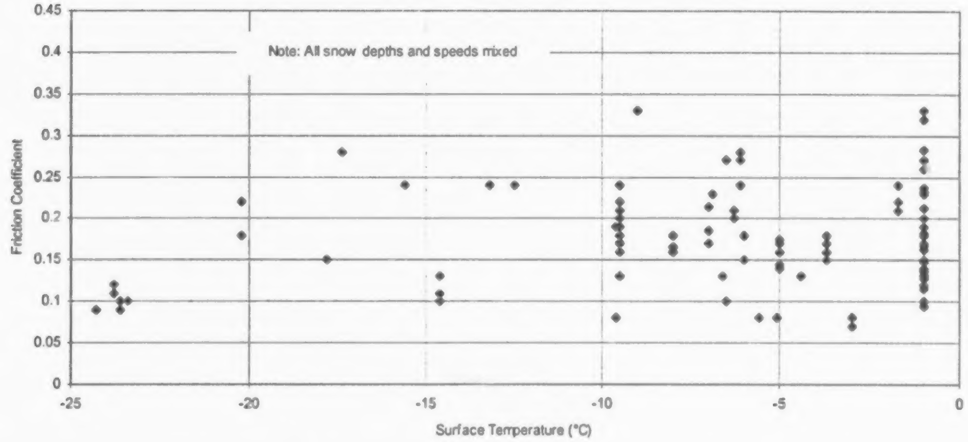
E.1-14: IMAG Torque (Configurations 3 and 7) Readings for Snow on Ice Including Rough Ice: Effect of Temperature

APPENDIX E.2

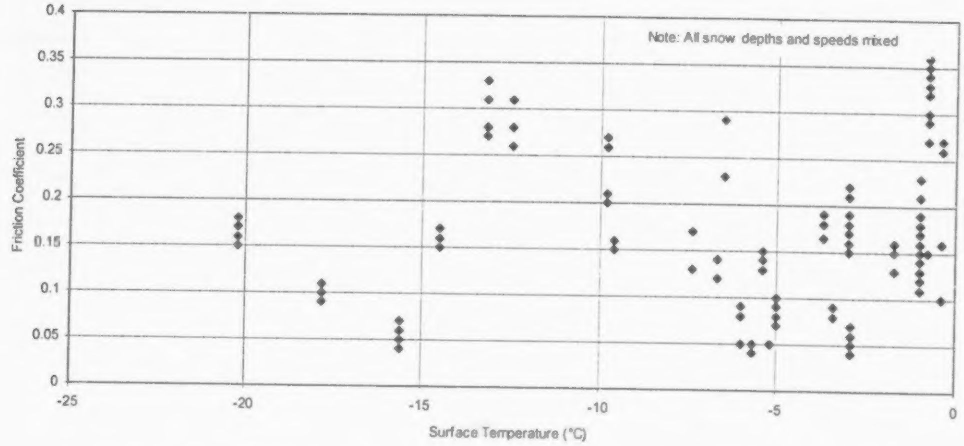
TRENDS PLOTS VS. SURFACE TEMPERATURE
(ALL SNOW DEPTHS)



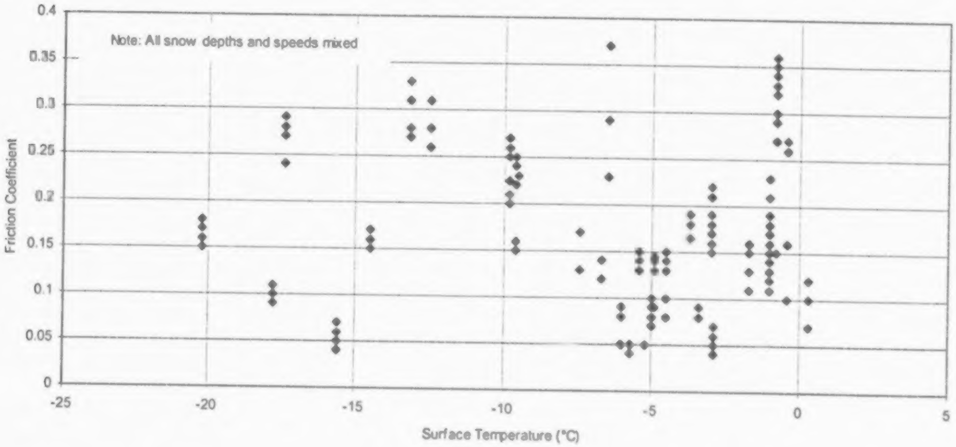
E.2-1: ERD Readings for Snow on an Ice Base: Effect of Surface Temperature



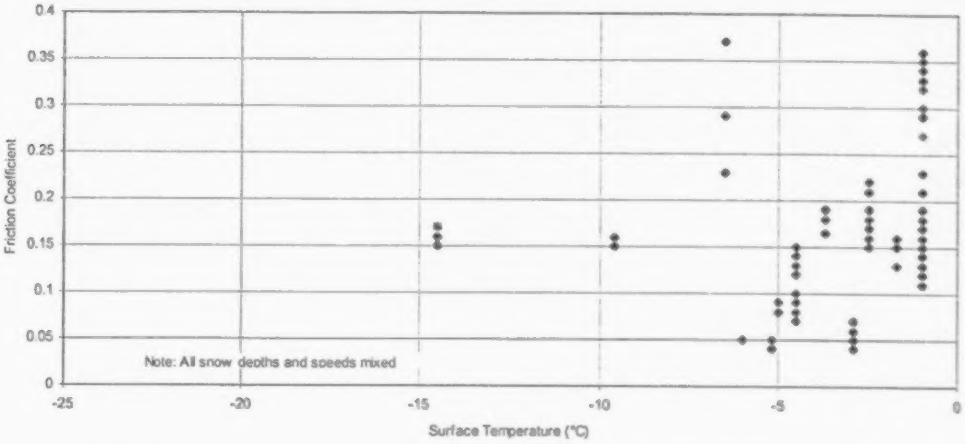
E.2-2: ERD Readings for Snow on Ice Including Rough Ice:
Effect of Surface Temperature



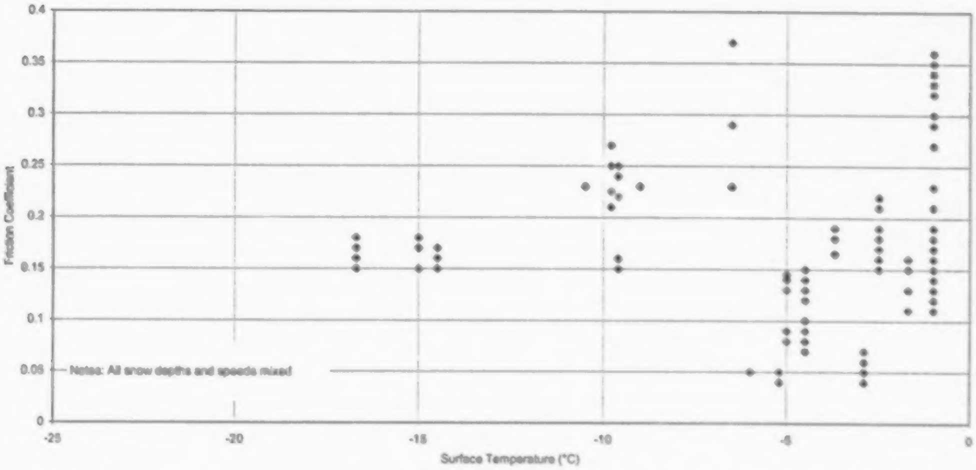
E.2-3: TC SFT'79 (All Configurations) Readings for Snow on an Ice Base: Effect of Surface Temperature



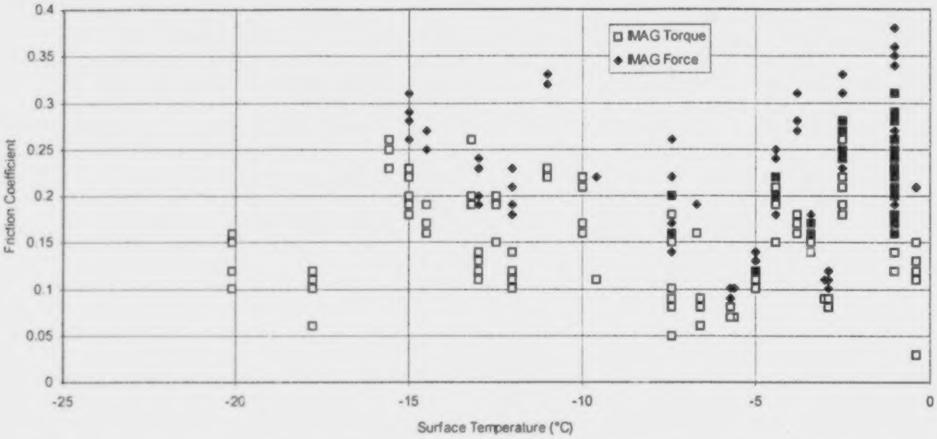
E.2-4: TC SFT'79 (All Configurations) Readings for Snow on Ice Including Rough Ice: Effect of Surface Temperature



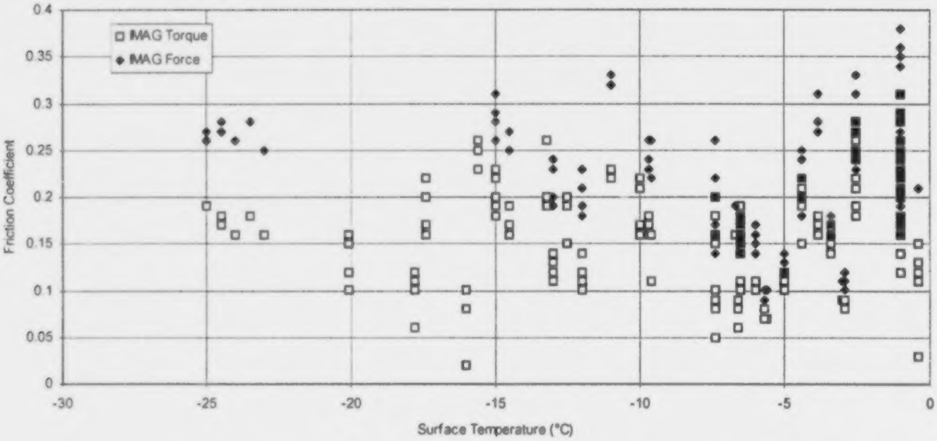
E.2-5: TC SFT'79 (Configuration 3) Readings for Snow on an Ice Base: Effect of Surface Temperature



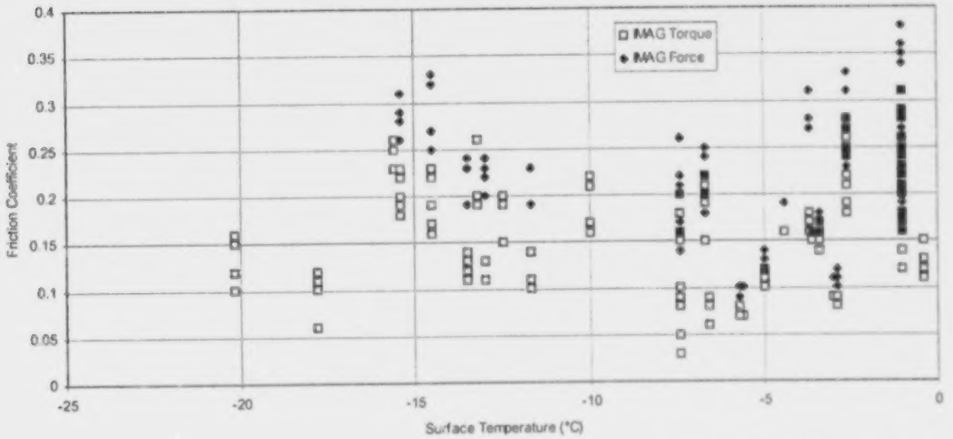
E.2-6: TC SFT'79 (Configuration 3) Readings for Snow on Ice Including Rough Ice: Effect of Surface Temperature



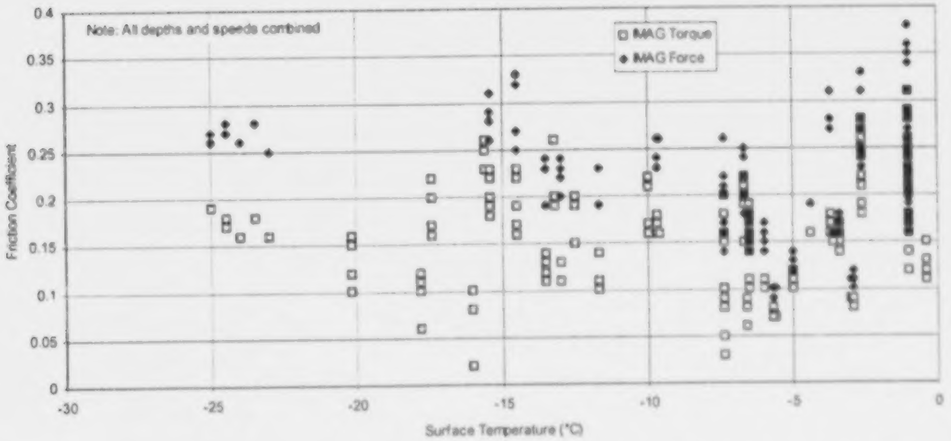
E.2-7: Effect of Temperature: IMAG (All Configurations) Readings for Snow on Ice



E.2-8: Effect of Temperature: IMAG (All Configurations) Readings for Snow on Ice Including Rough Ice



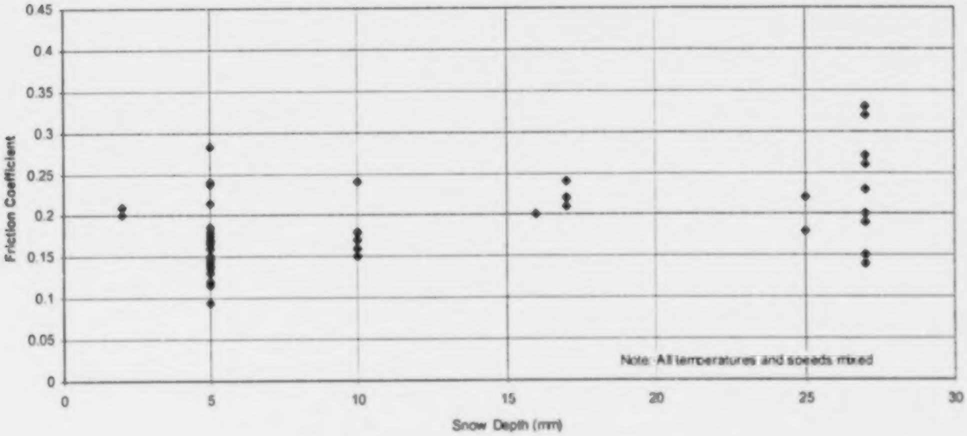
E.2-9: Effect of Temperature: IMAG (Configurations 3 and 7) Readings for Snow on Ice



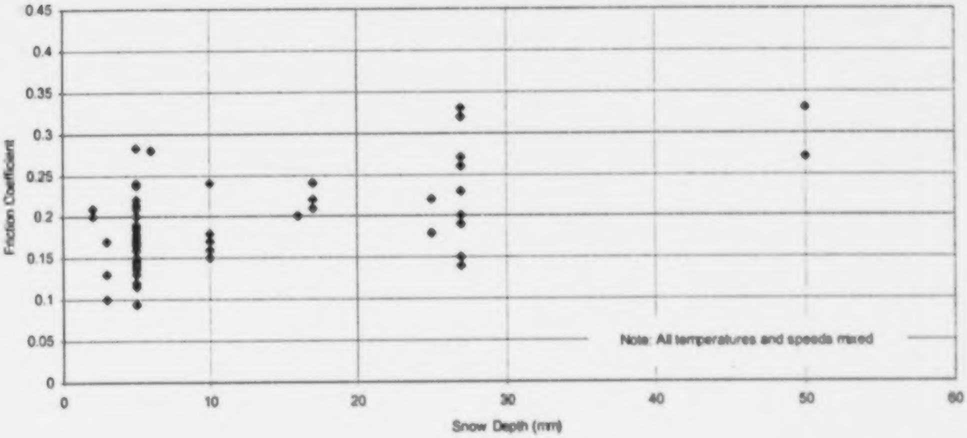
E.2-10: Effect of Temperature: IMAG (Configurations 3 and 7) Readings for Snow on Ice Including Rough Ice

APPENDIX E.3

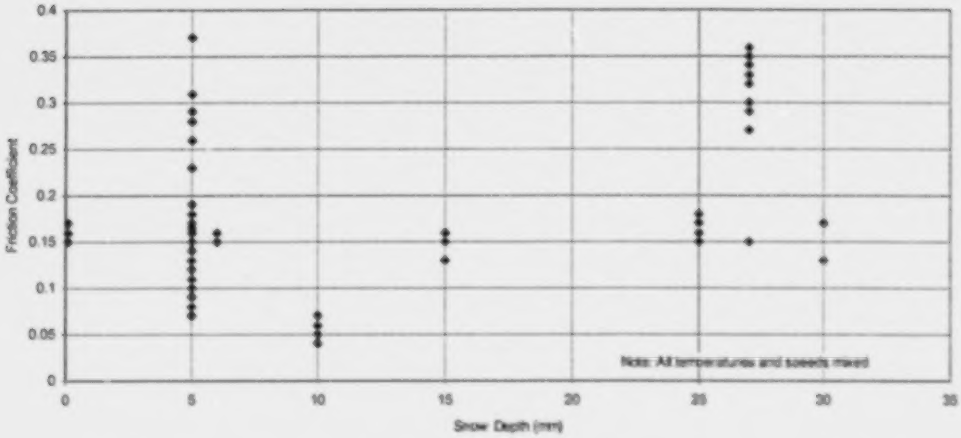
TREND PLOTS VS. SNOW DEPTH
(ALL SNOW DEPTHS)



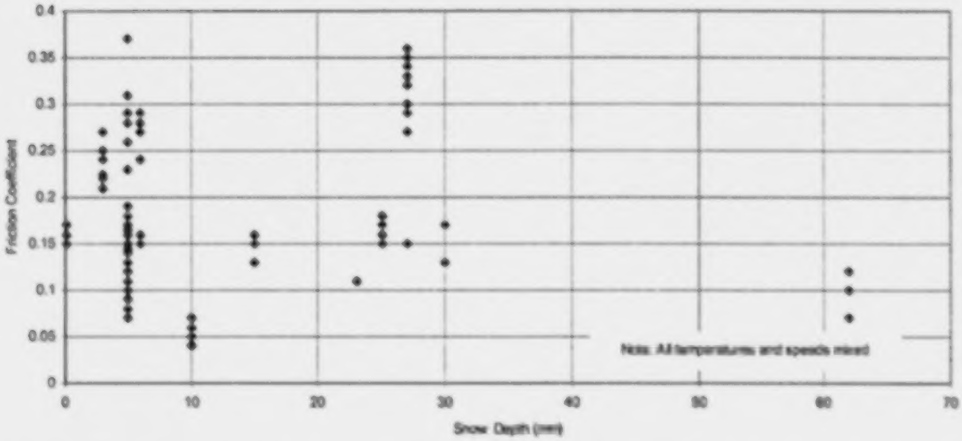
E.3-1: ERD Readings for Snow on an Ice Base: Effect of Snow Base



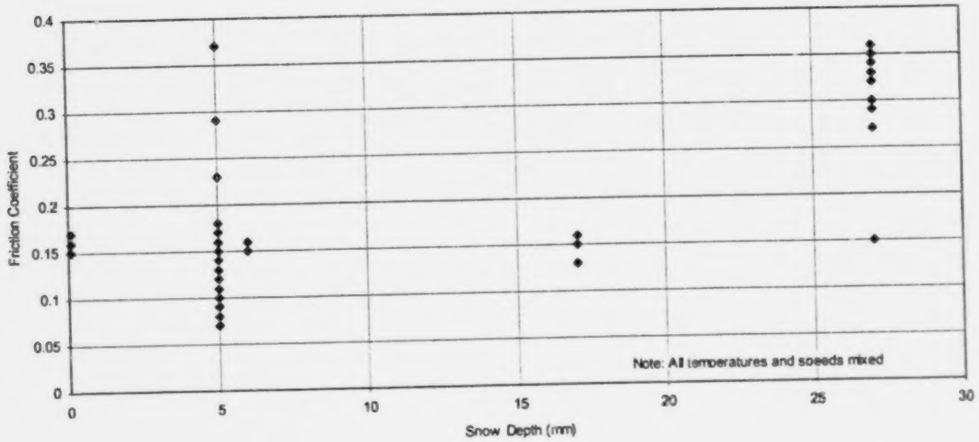
E.3-2: ERD Readings for Snow on Ice Including Rough Ice: Effect of Snow Depth



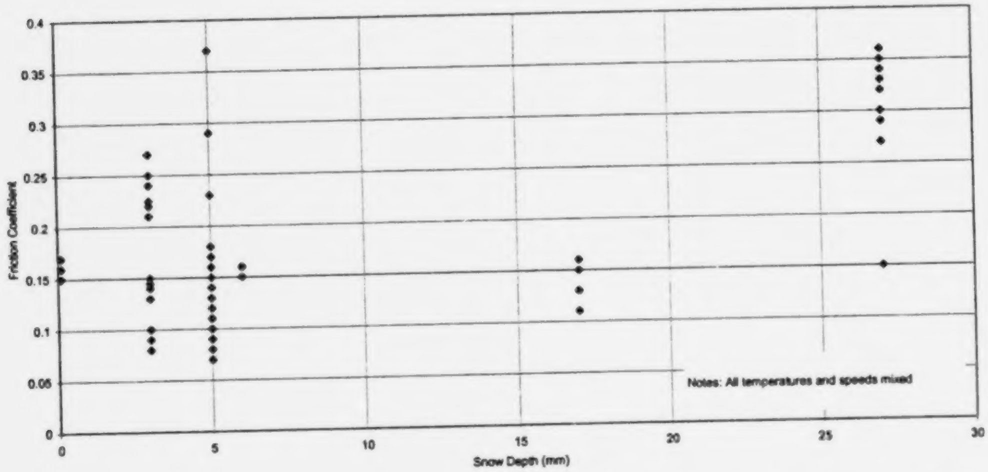
E.3-3: TC SFT'79 (All Configurations) Readings for Snow on an Ice Base: Effect of Snow Depth



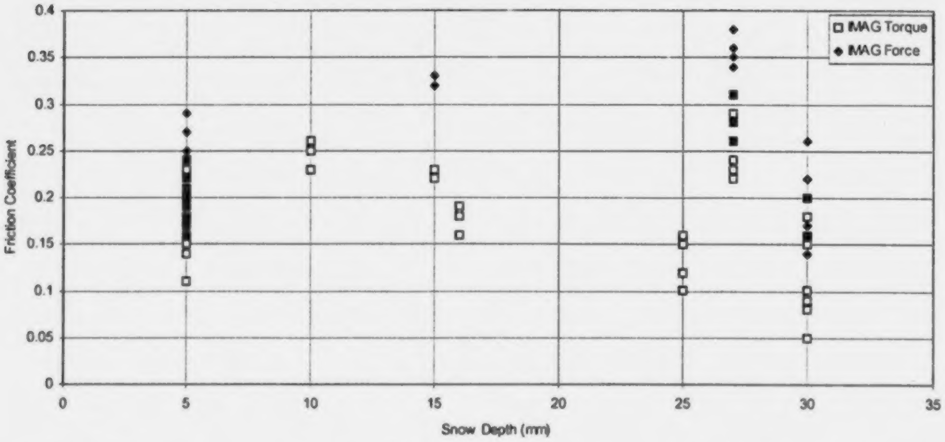
E.3-4: TC SFT'79 (All Configurations) Readings for Snow on Ice Including Rough Ice: Effect of Snow Depth



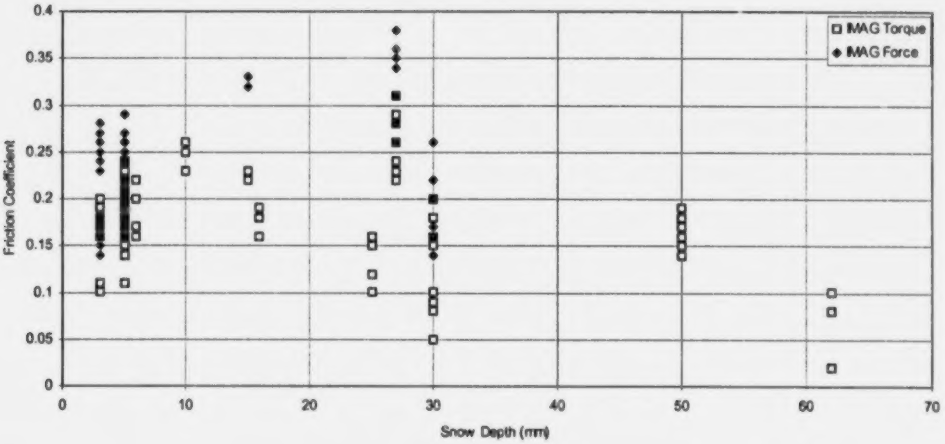
E.3-5: TC SFT'79 (Configuration 3) Readings for Snow on an Ice Base: Effect of Snow Depth



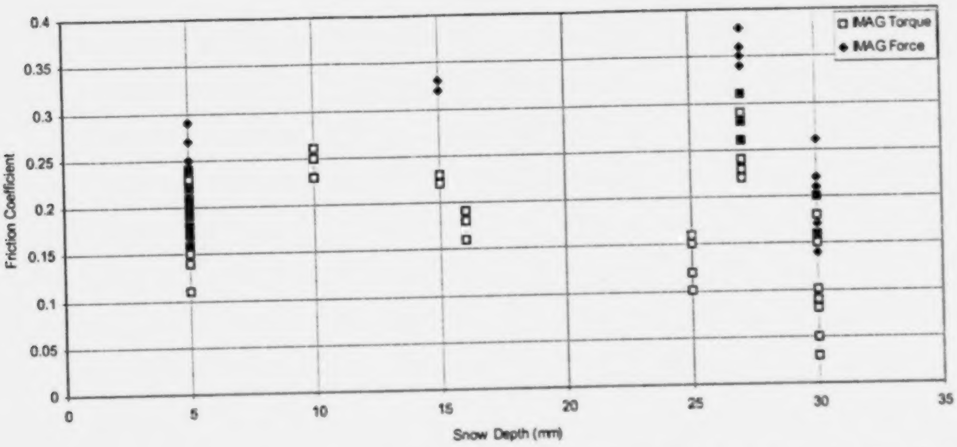
E.3-6: TC SFT'79 (Configuration 3) Readings for Snow on Ice Including Rough Ice: Effect of Snow Depth



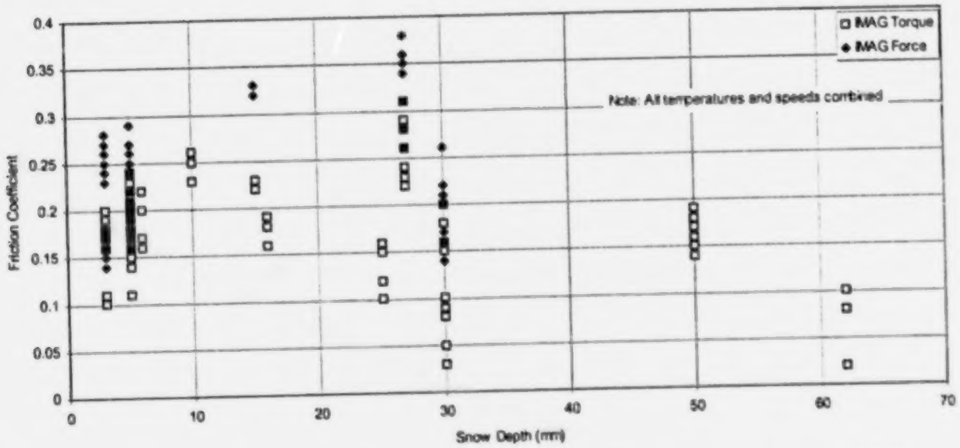
E.3-7: Effect of Snow Depth: IMAG (All Configurations) Readings for Snow on Ice



E.3-8: Effect of Snow Depth: IMAG (All Configurations) Readings for Snow on Ice Including Rough Ice



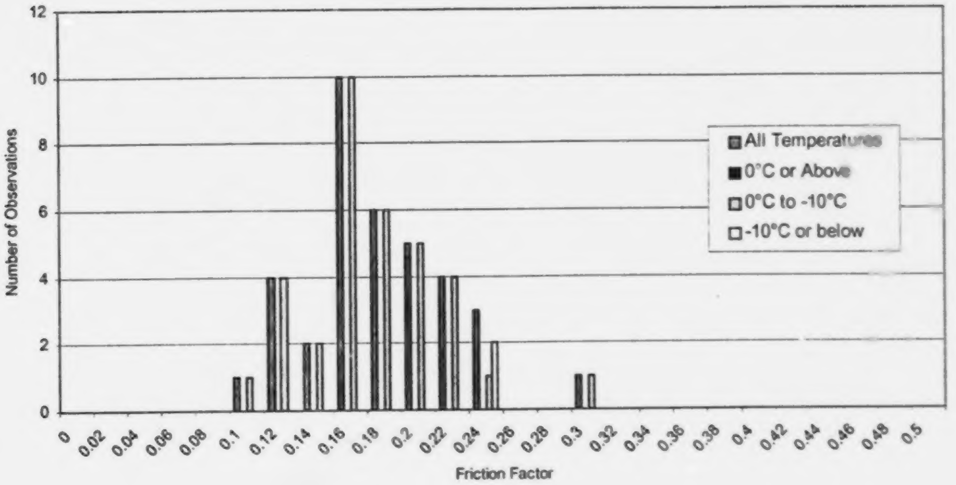
E.3-9: Effect of Snow Depth: IMAG (Configurations 3 and 7) Readings for Snow on Ice



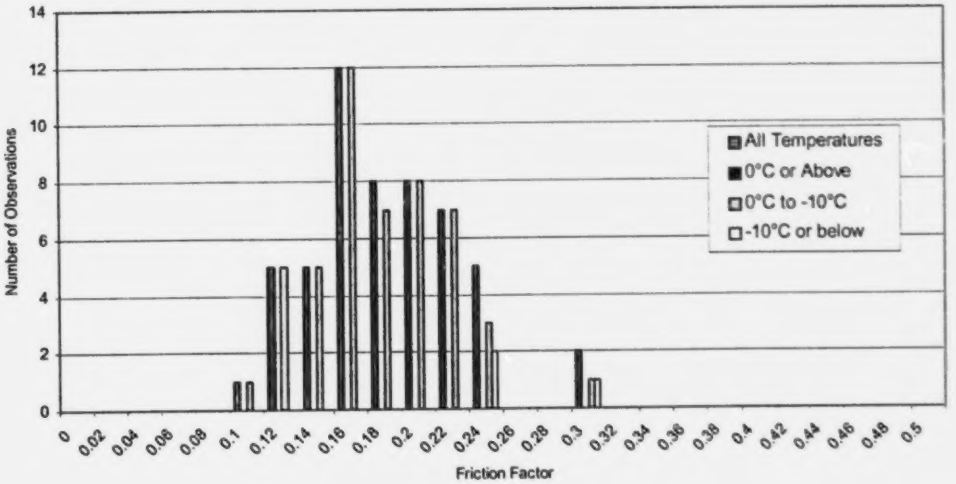
E.3-10: Effect of Snow Depth: IMAG (Configurations 3 and 7) Readings for Snow on Ice Including Rough Ice

APPENDIX E.4

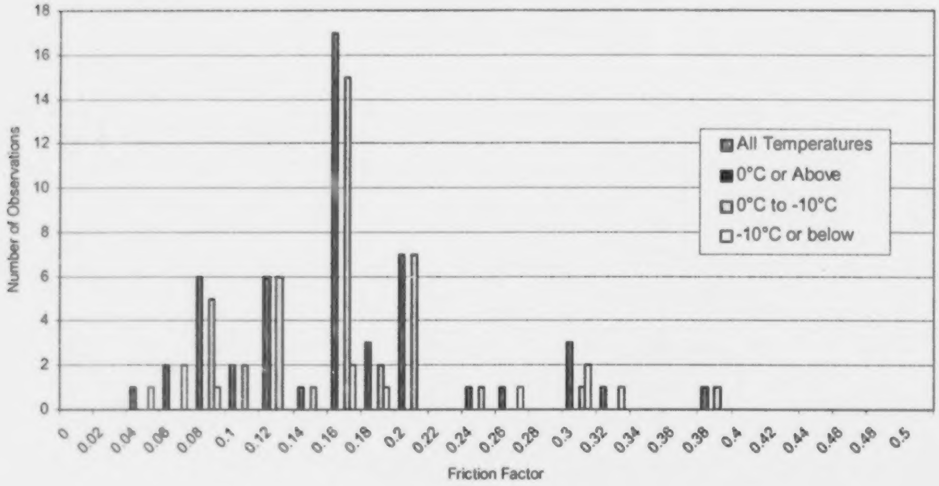
HISTOGRAMS FOR SNOW ON ICE
(SNOW DEPTHS 10 MM OR LESS)



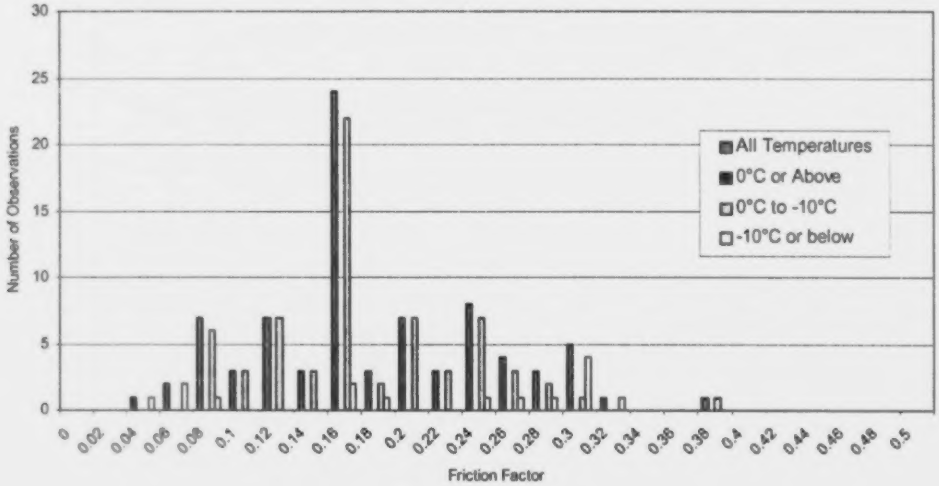
E.4-1: ERD Readings for Snow on an Ice Base: Effect of Temperature



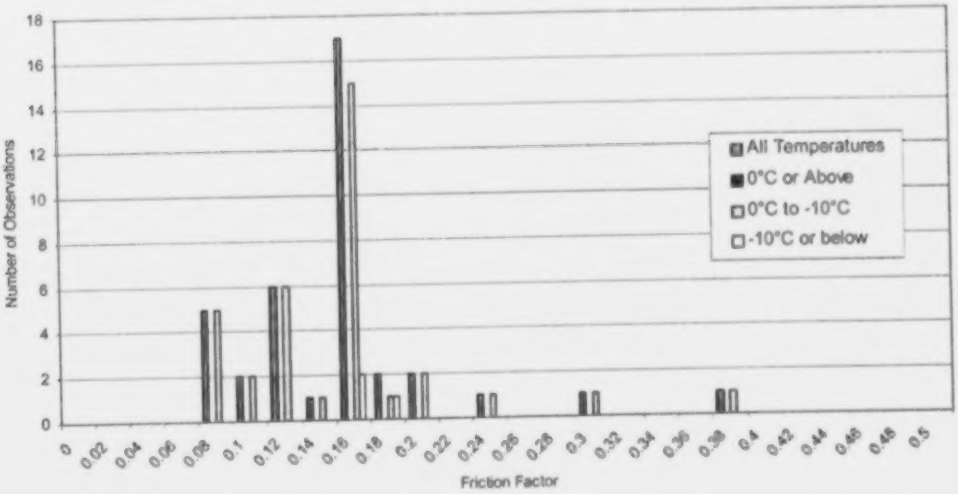
E.4-2: ERD Readings for Snow on Ice Including Rough Ice: Effect of Temperature



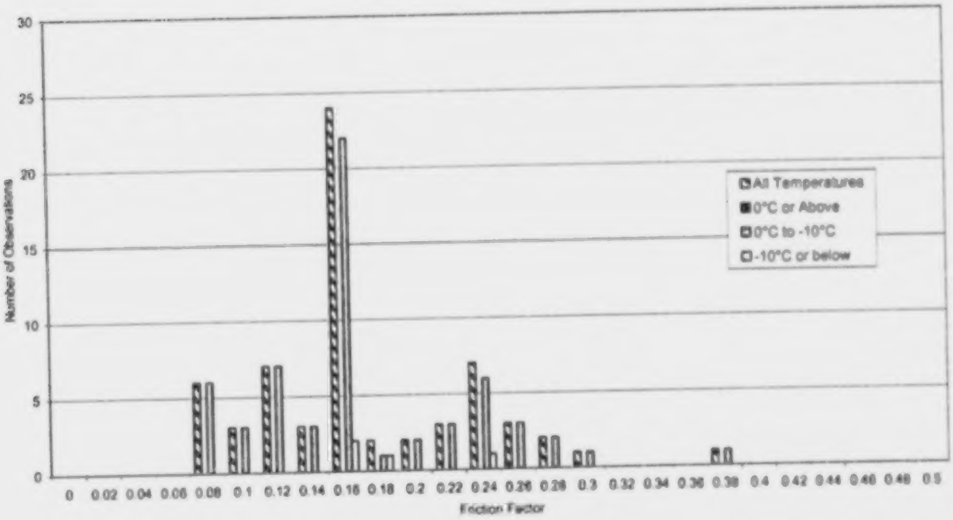
E.4-3: TC SFT'79 (All Configurations) Readings for Snow on an Ice Base: Effect of Temperature



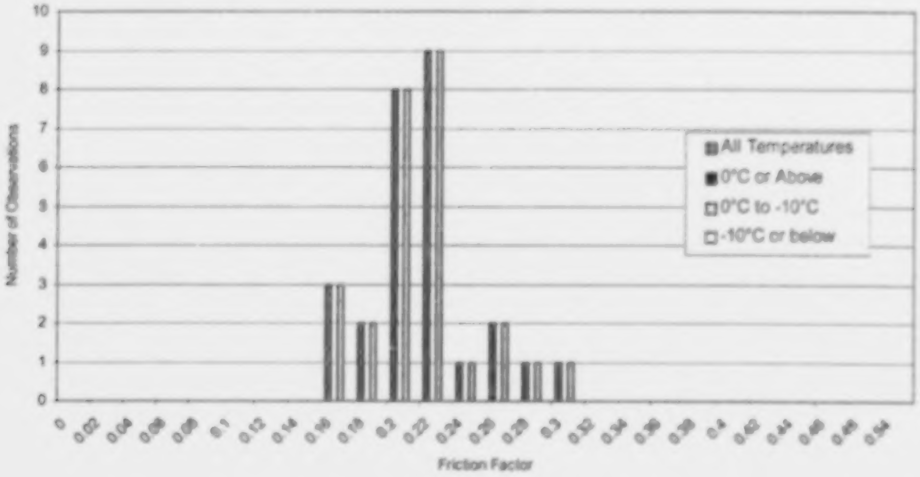
E.4-4: TC SFT'79 (All Configurations) Readings for Snow on Ice Including Rough Ice: Effect of Temperature



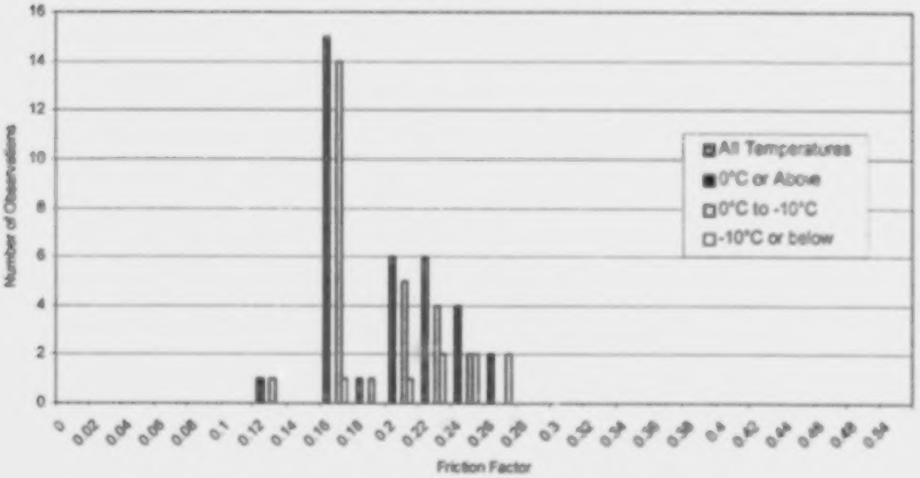
E.4-5: TC SFT'79 (Configuration 3) Readings for Snow on an Ice Base: Effect of Temperature



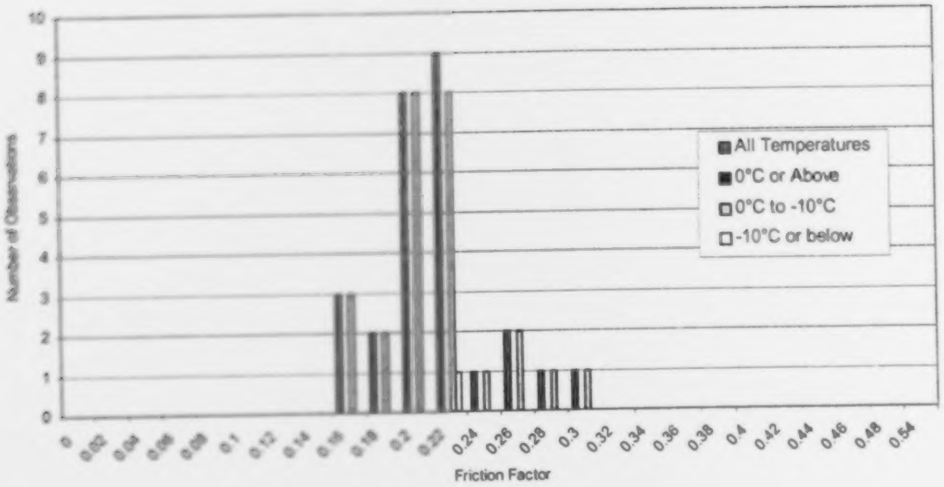
E.4-6: TC SFT'79 (Configuration 3) Readings for Snow on Ice Including Rough Ice: Effect of Temperature



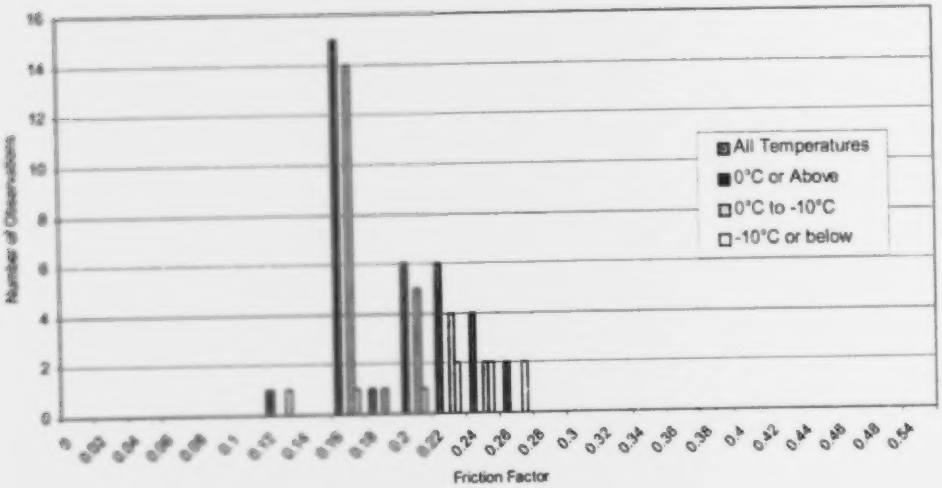
E.4-7: IMAG Force (All Configurations) Readings for Snow on Bare Ice: Effect of Temperature



E.4-8: IMAG Torque (All Configurations) Readings for Snow on Bare Ice: Effect of Temperature



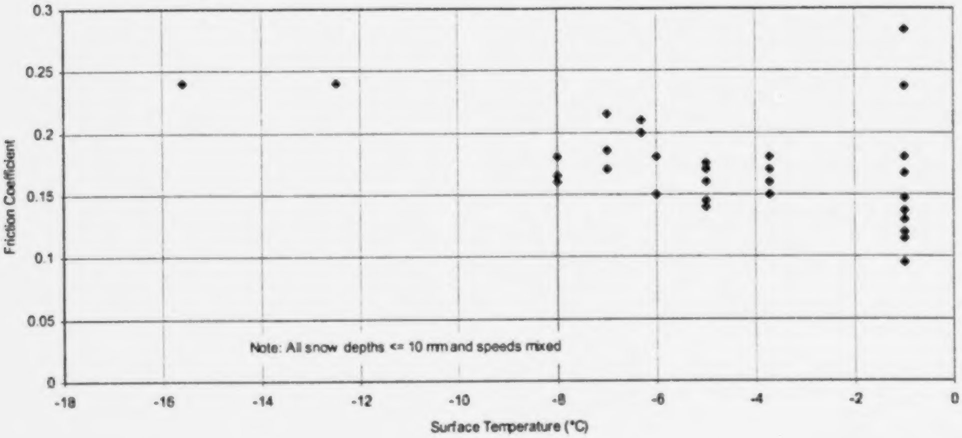
E.4-9: IMAG Force (Configurations 3 and 7) Readings for Snow on Bare Ice: Effect of Temperature



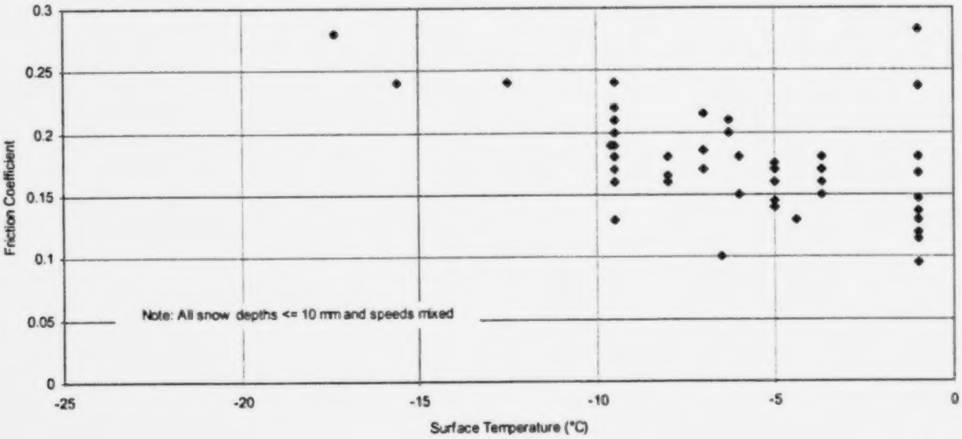
E.4-10: IMAG Torque (Configurations 3 and 7) Readings for Snow on Bare Ice: Effect of Temperature

APPENDIX E.5

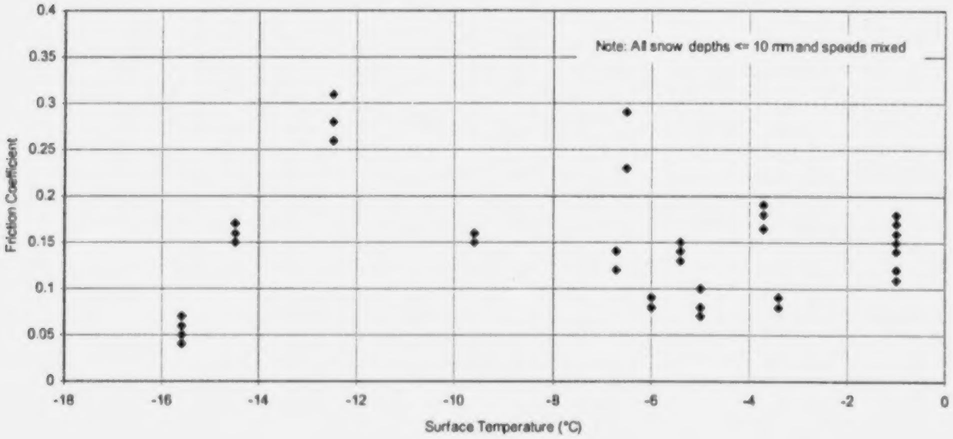
TREND PLOTS VS. SURFACE TEMPERATURE
(SNOW DEPTHS 10 MM OR LESS)



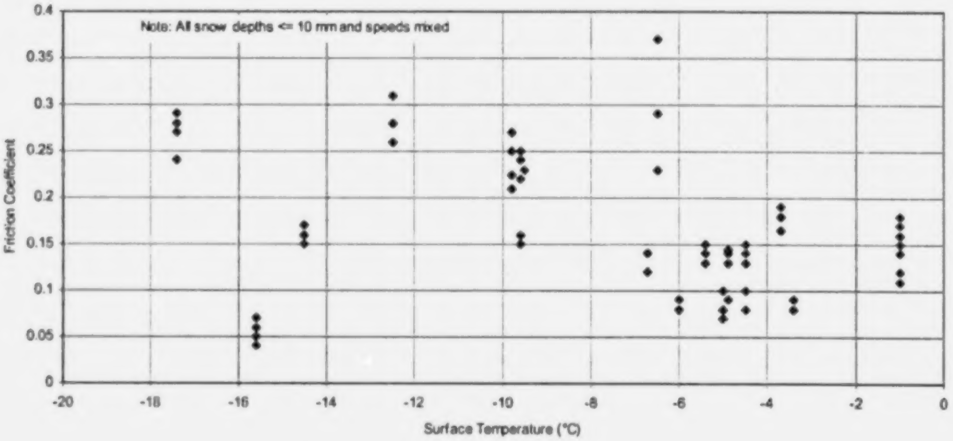
E.5-1: ERD Readings for Snow on an Ice Base: Effect of Surface Temperature



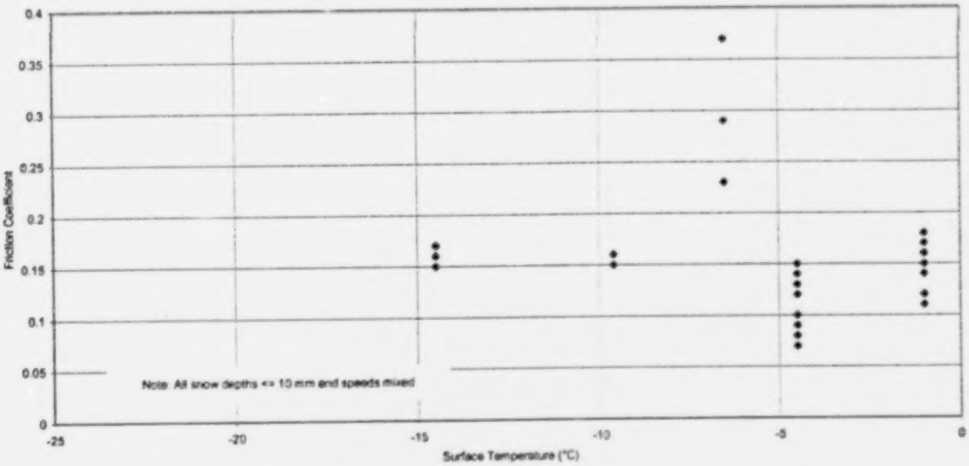
E.5-2: ERD Readings for Snow on Ice Including Rough Ice: Effect of Surface Temperature



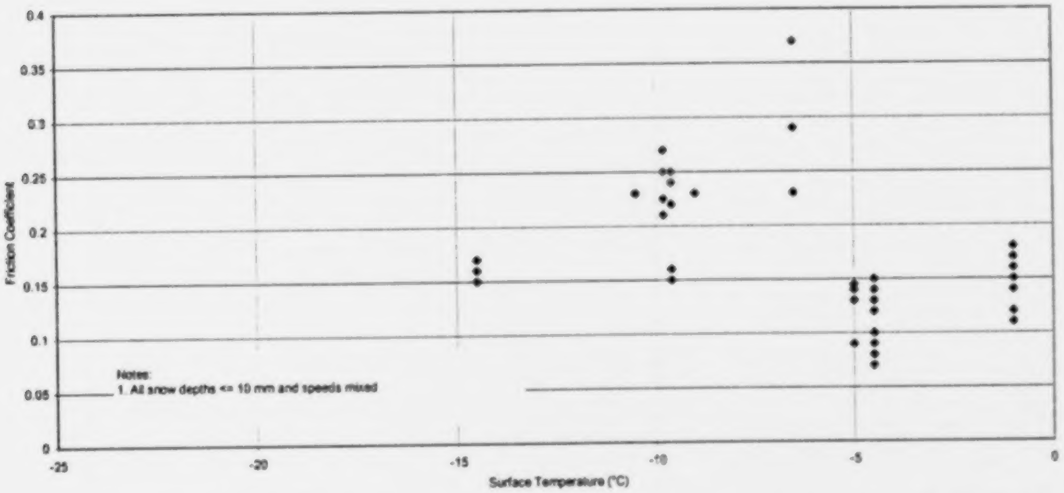
E.5-3: TC SFT'79 (All Configurations) Readings for Snow on an Ice Base: Effect of Surface Temperature



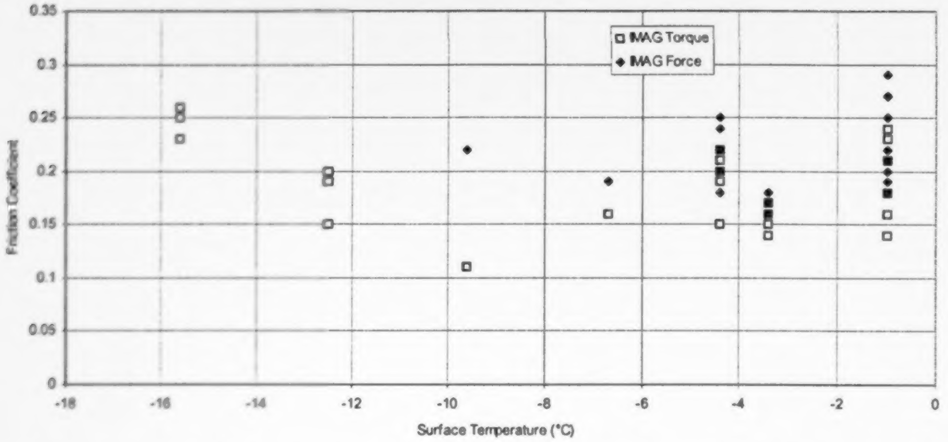
E.5-4: TC SFT'79 (All Configurations) Readings for Snow on Ice Including Rough Ice: Effect of Surface Temperature



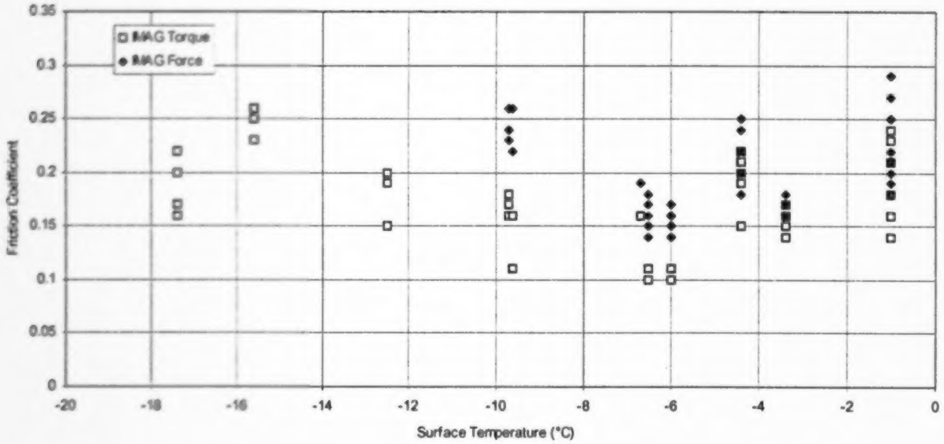
E.5-5: TC SFT'79 (Configuration 3) Readings for Snow on an Ice Base: Effect of Surface Temperature



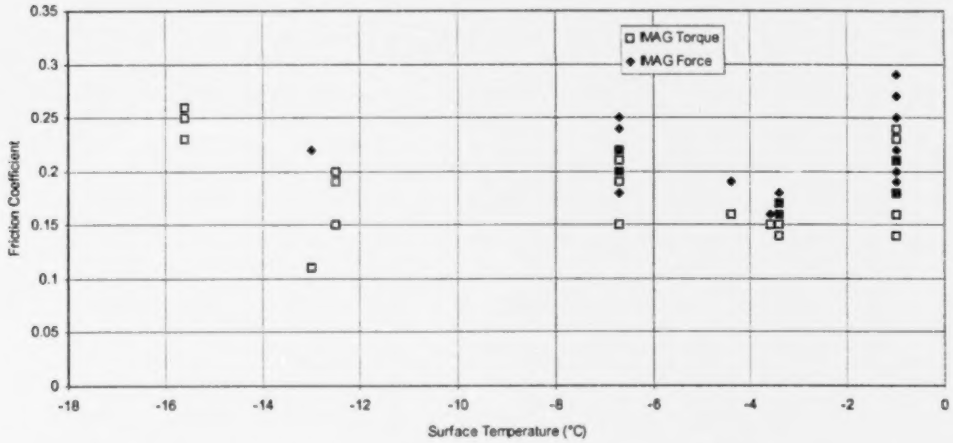
E.5-6: TC SFT'79 (Configuration 3) Readings for Snow on Ice Including Rough Ice: Effect of Surface Temperature



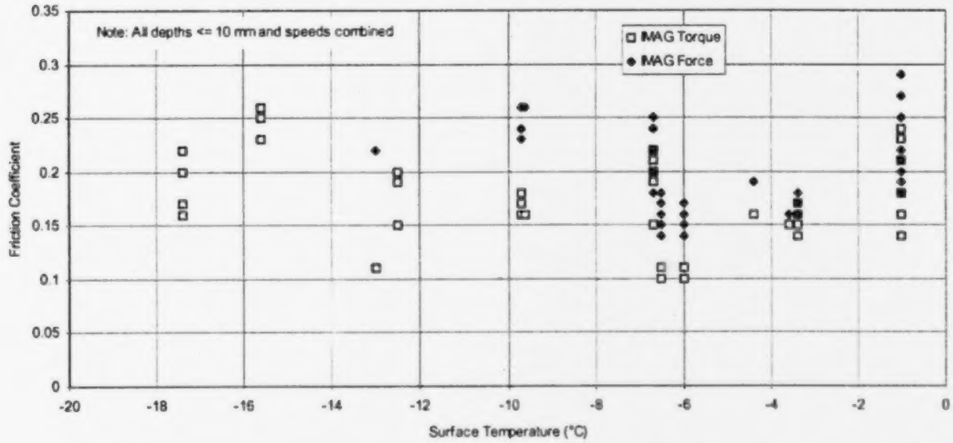
E.5-7: Effect of Temperature: IMAG (All Configurations) Readings for Snow on Ice



E.5-8: Effect of Temperature: IMAG (All Configurations) Readings for Snow on Ice Including Rough Ice



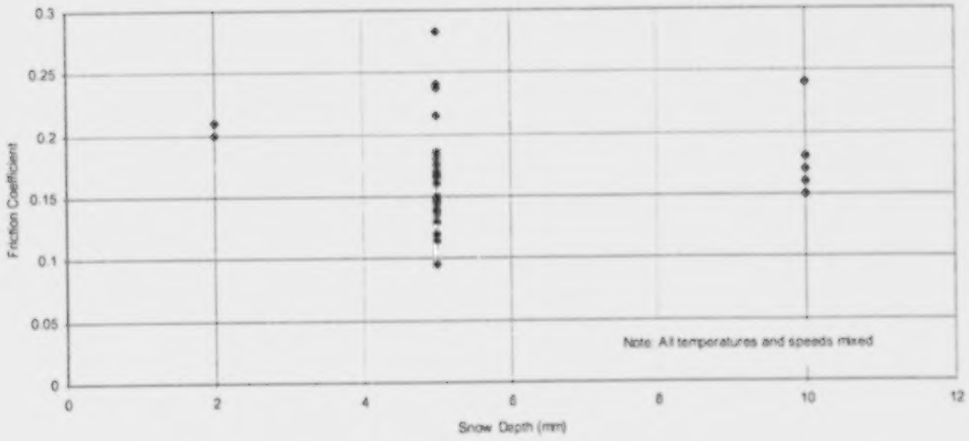
E.5-9: Effect of Temperature: IMAG (Configurations 3 and 7) Readings for Snow on Ice



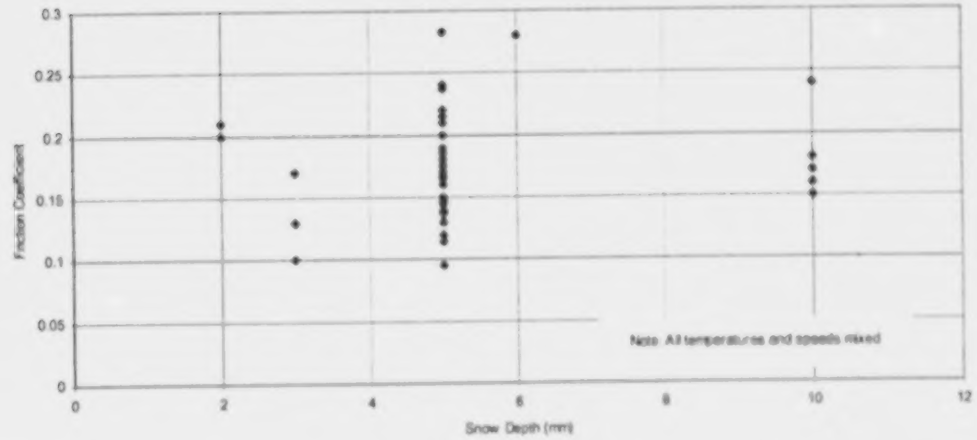
E.5-10: Effect of Temperature: IMAG (Configurations 3 and 7) Readings for Snow on Ice Including Rough Ice

APPENDIX E.6

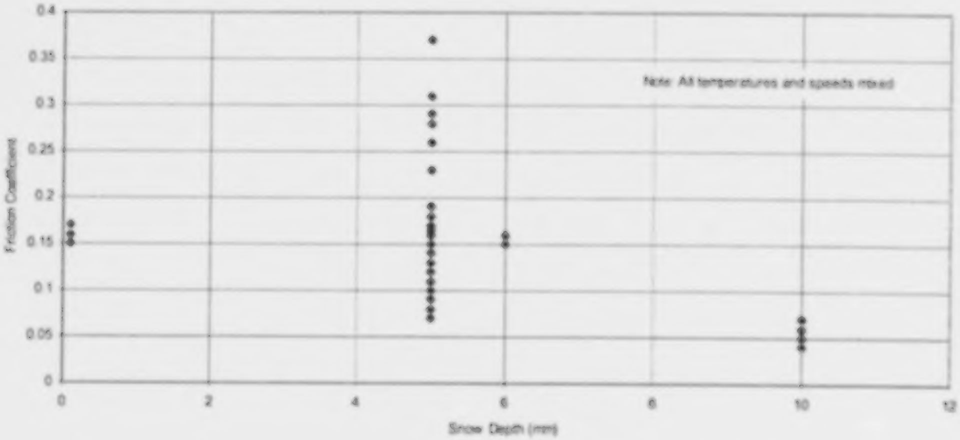
TREND PLOTS VS. SNOW DEPTH
(SNOW DEPTHS 10 MM OR LESS)



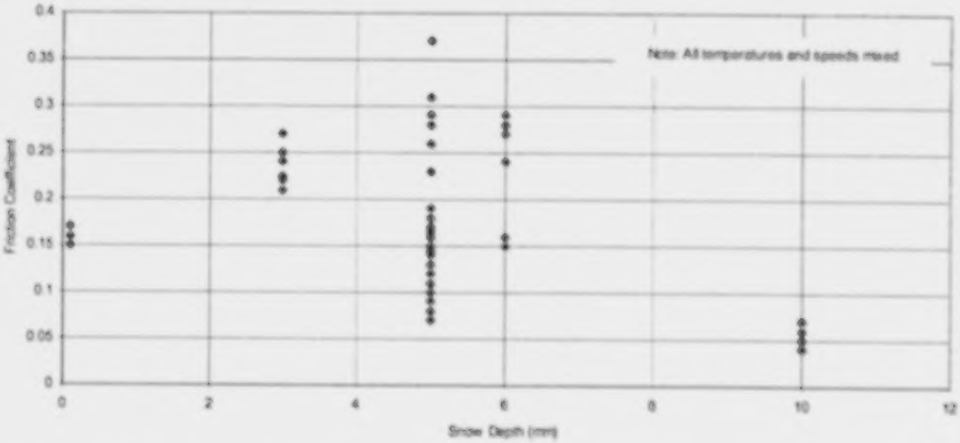
E.6-1: ERD Readings for Snow on an Ice Base: Effect of Snow Depth



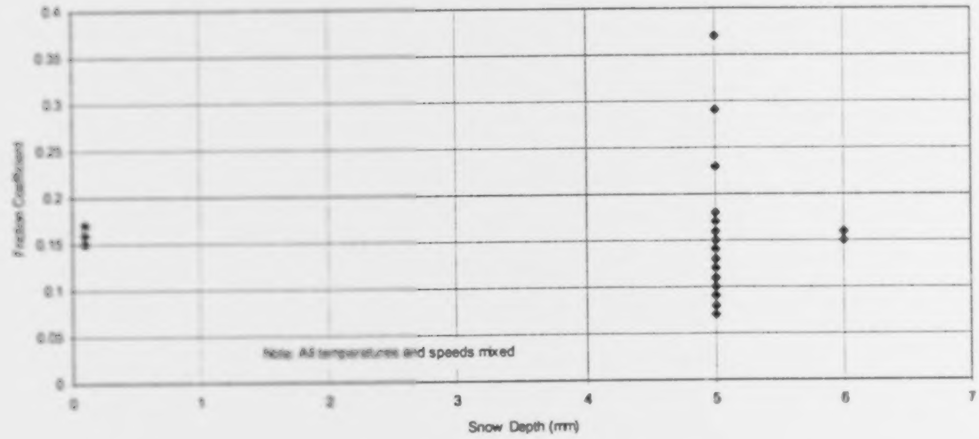
E.6-2: ERD Readings for Snow on Ice Including Rough Ice: Effect of Snow Depth



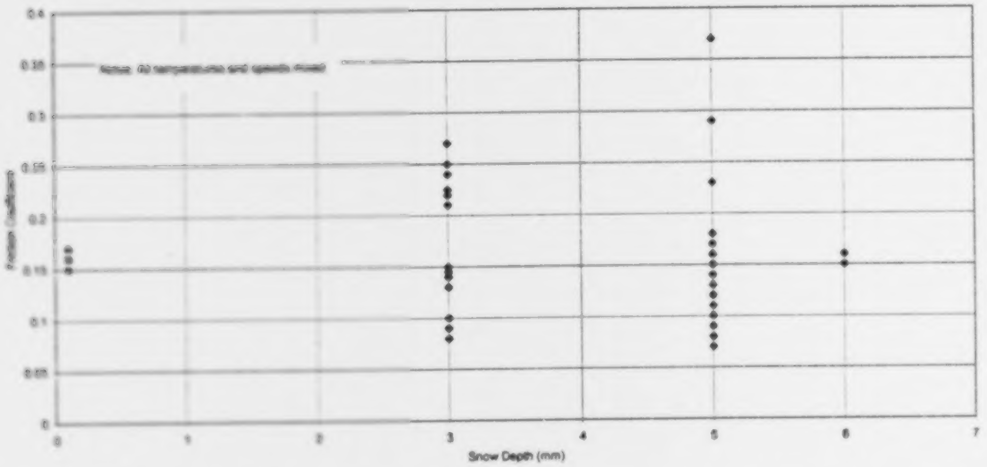
E.6-3: TC SFT'79 (All Configurations) Readings for Snow on an Ice Base: Effect of Snow Depth



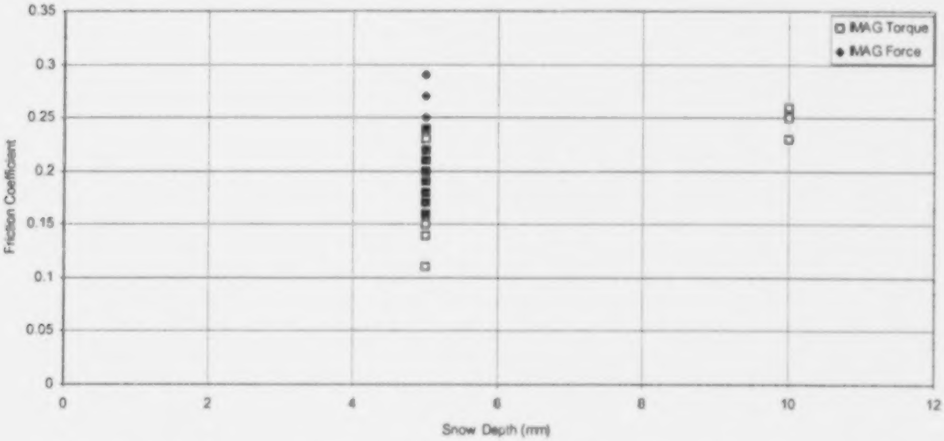
E.6-4: TC SFT'79 (All Configurations) Readings for Snow on Ice Including Rough Ice: Effect of Snow Depth



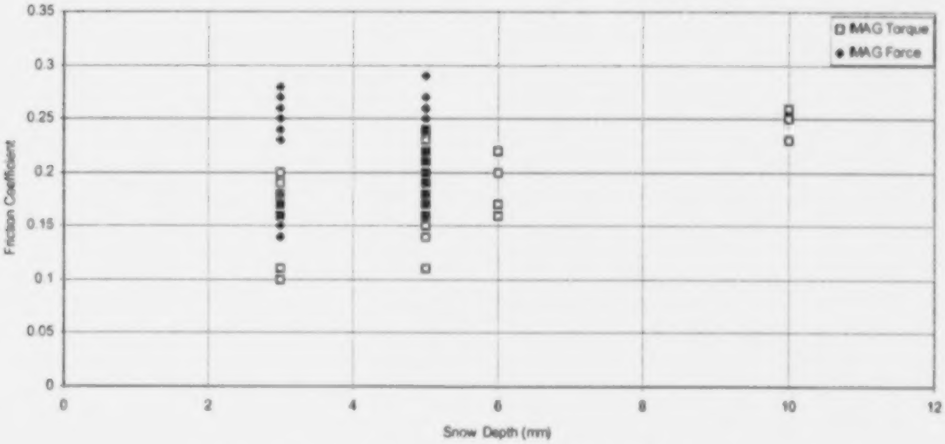
E.6-5: TC SFT'79 (Configuration 3) Readings for Snow on an Ice Base: Effect of Snow Depth



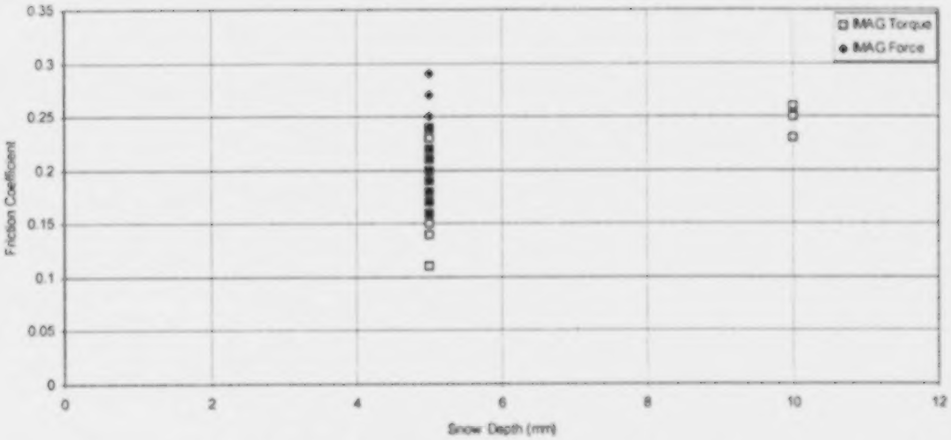
E.6-6: TC SFT'79 (Configuration 3) Readings for Snow on Ice Including Rough Ice: Effect of Snow Depth



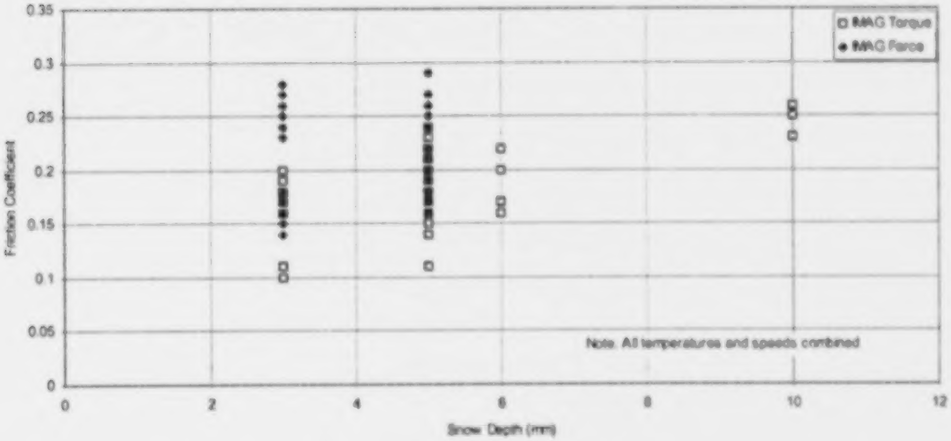
E.6-7: Effect of Snow Depth: IMAG (All Configurations) Readings for Snow on Ice



E.6-8: Effect of Snow Depth: IMAG (All Configurations) Readings for Snow on Ice Including Rough Ice



E.6-9: Effect of Snow Depth: IMAG (Configurations 3 and 7) Readings for Snow on Ice



E.6-10: Effect of Snow Depth: IMAG (Configurations 3 and 7) Readings for Snow on Ice Including Rough Ice

APPENDIX F

RESULTS FOR SNOW ON PACKED SNOW

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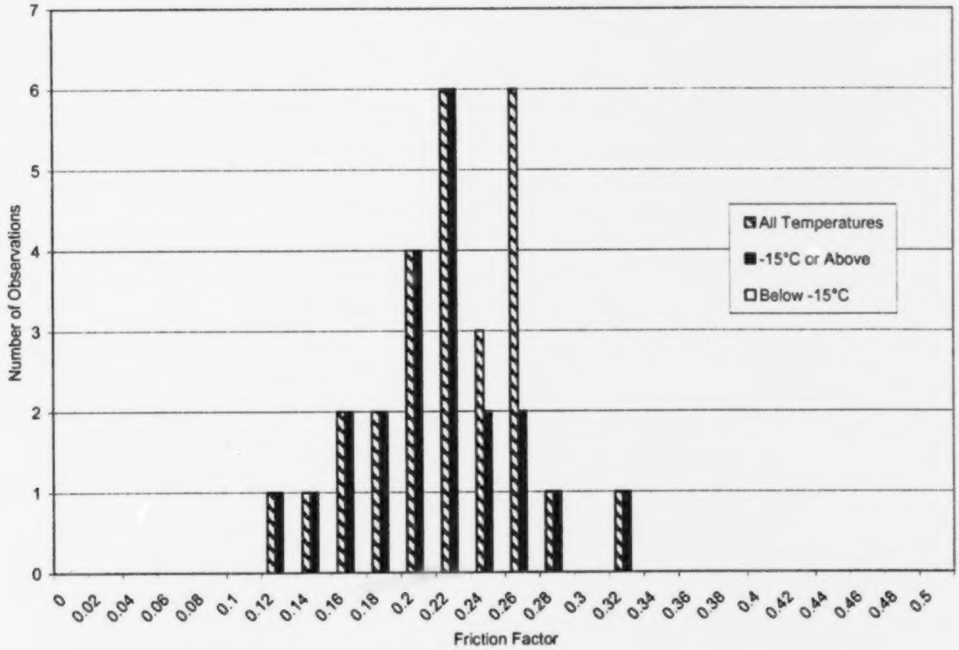
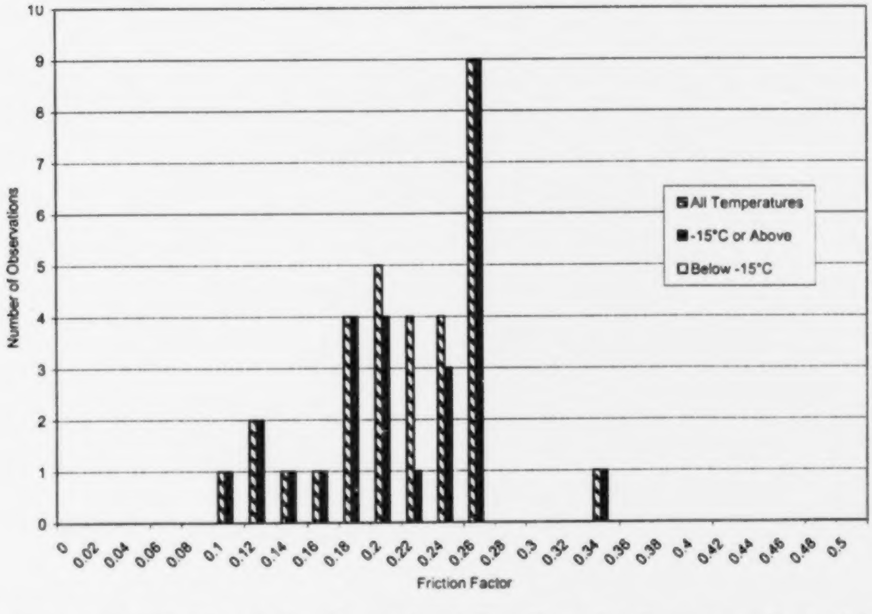
Appendix F.5: Trend Plots vs. Surface Temperature (Snow Depths 10 mm or Less)
Appendix F.6: Trend Plots vs. Snow Depth (Snow Depths 10 mm or Less)

APPENDIX F.1

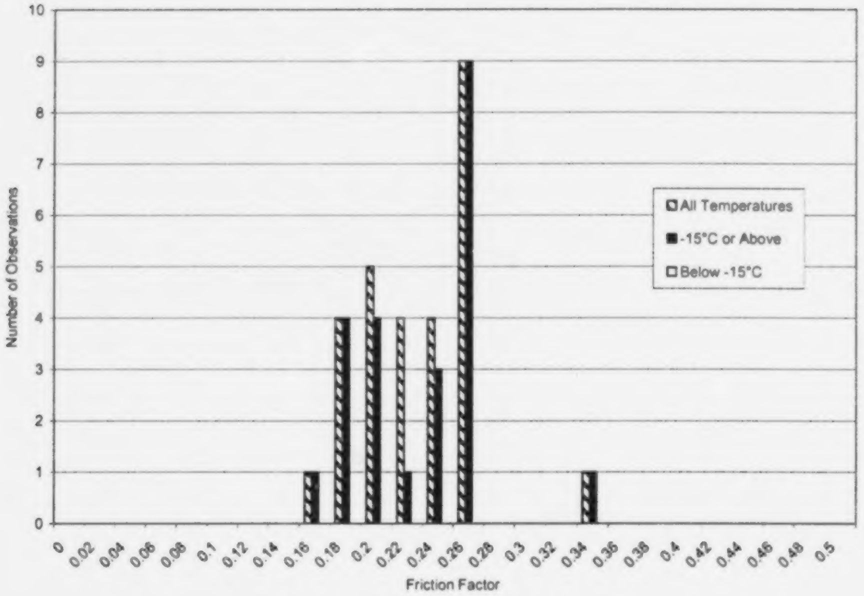
HISTOGRAMS
(ALL SNOW DEPTHS)



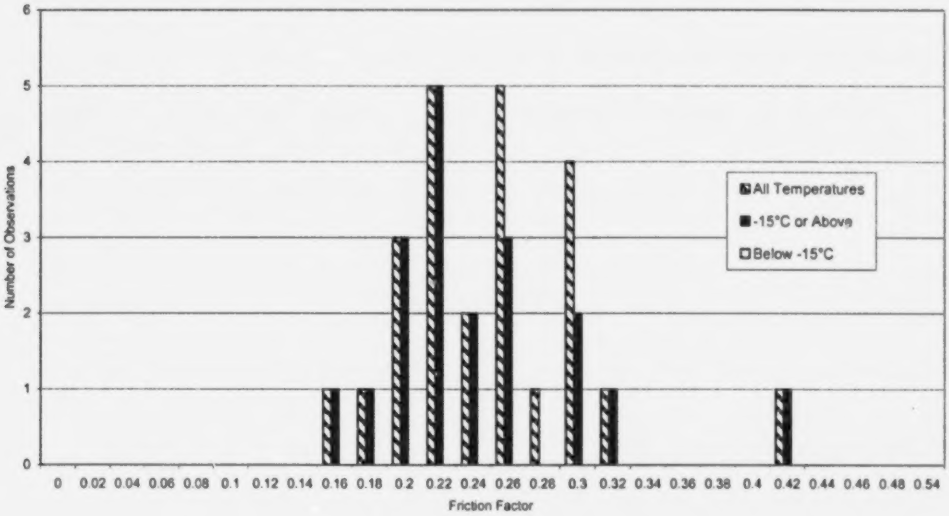
F.1-1: ERD Readings for Snow on a Packed Snow Base: Effect of Temperature



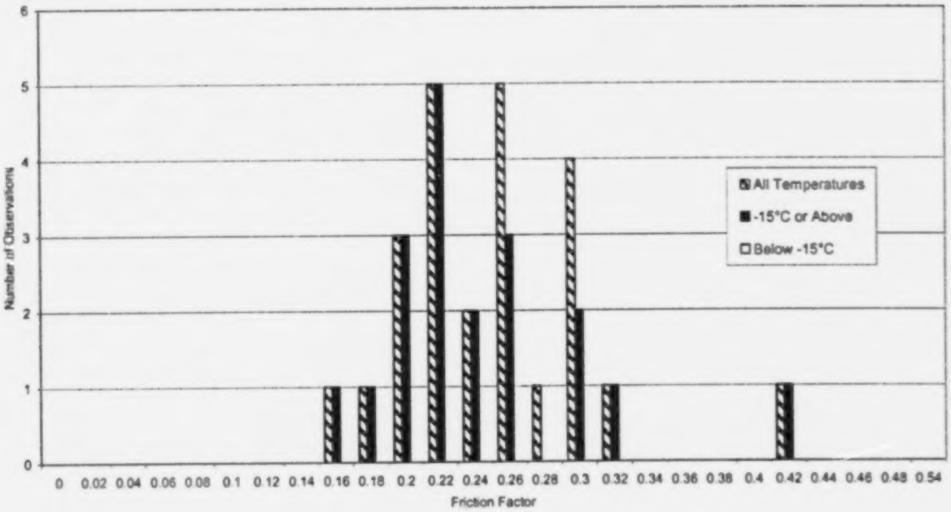
F.1-2: TC SFT'79 (All Configurations) Readings for Snow on a Packed Snow Base: Effect of Temperature



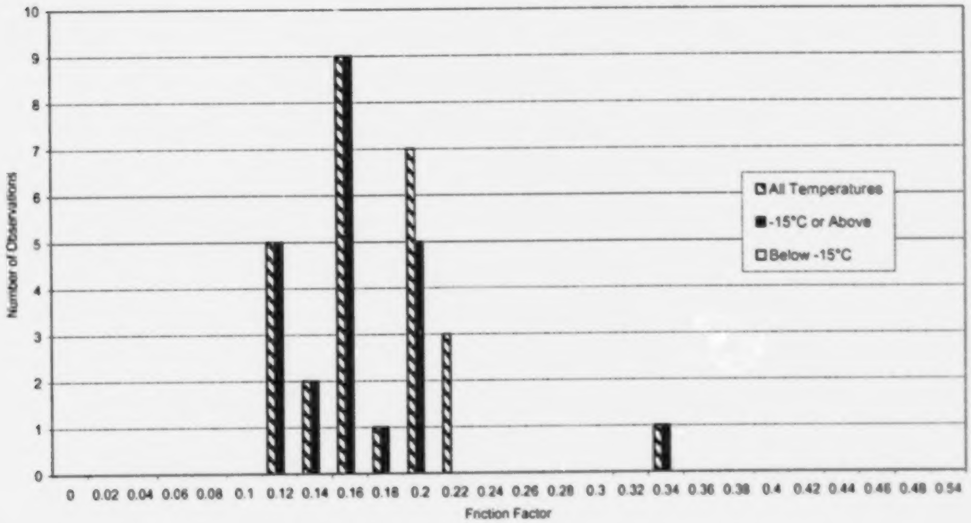
F.1-3: TC SFT'79 (Configuration 3) Readings for Snow on a Packed Snow Base: Effect of Temperature



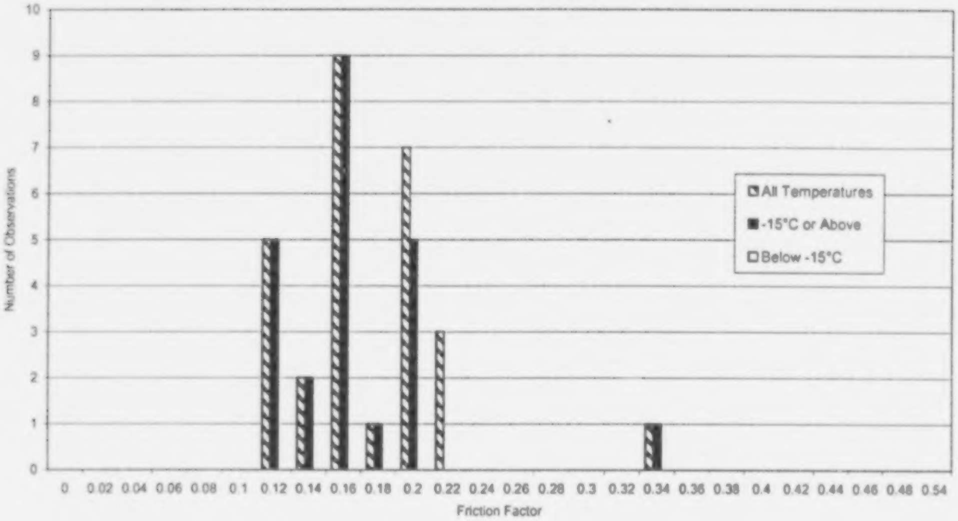
F.1-4: IMAG Force (All Configurations) Readings for Snow on Packed Snow: Effect of Temperature



F.1-5: IMAG Force (Configurations 3 and 7) Readings for Snow on Packed Snow: Effect of Temperature



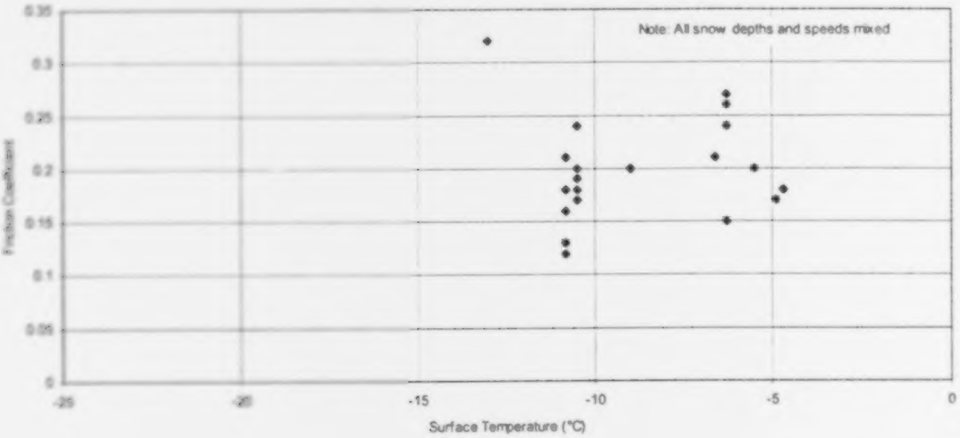
F.1-6: IMAG Torque (All Configurations) Readings for Snow on Packed Snow: Effect of Temperature



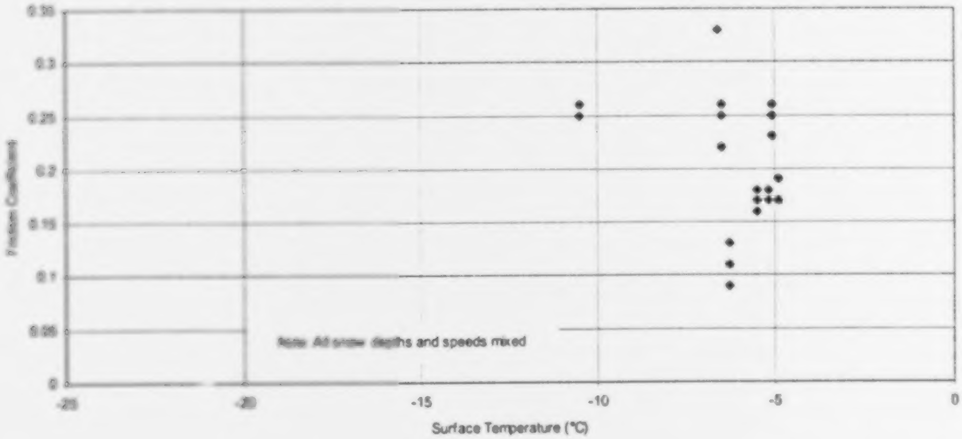
F.1-7: IMAG Torque (Configurations 3 and 7) Readings for Snow on Packed Snow: Effect of Temperature

APPENDIX F.2

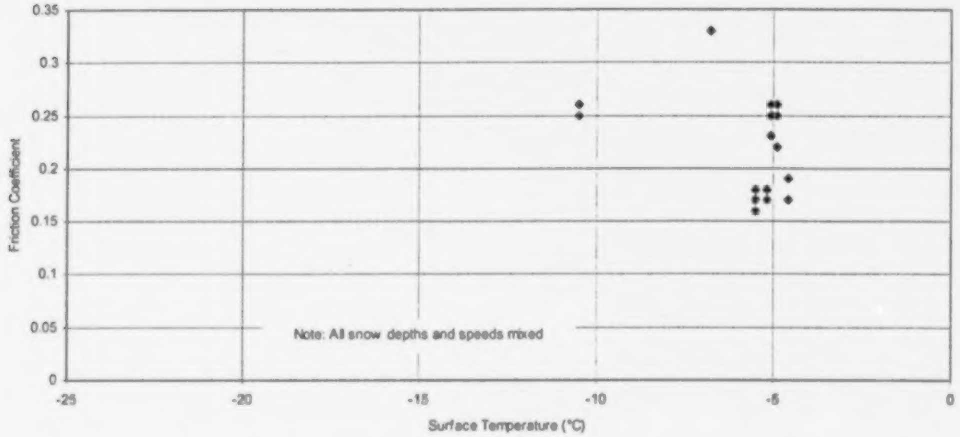
TREND PLOTS VS. SURFACE TEMPERATURE
(ALL SNOW DEPTHS)



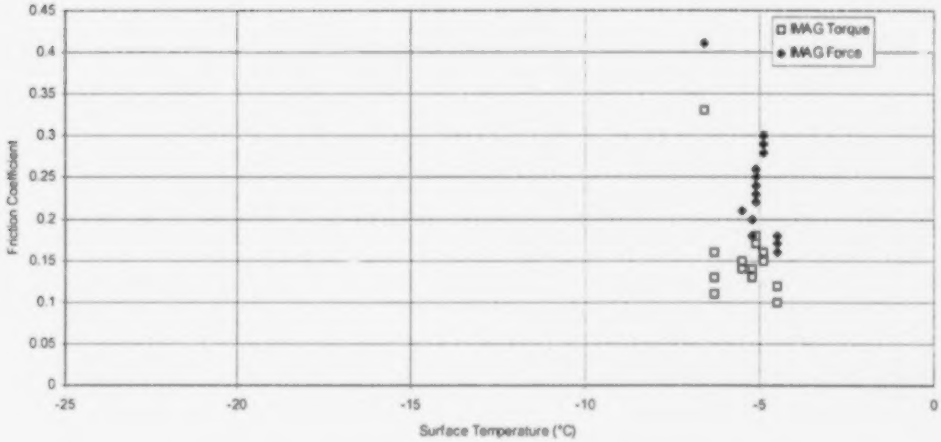
F.2-1: ERD Readings for Snow on a Packed Snow Base: Effect of Surface Temperature



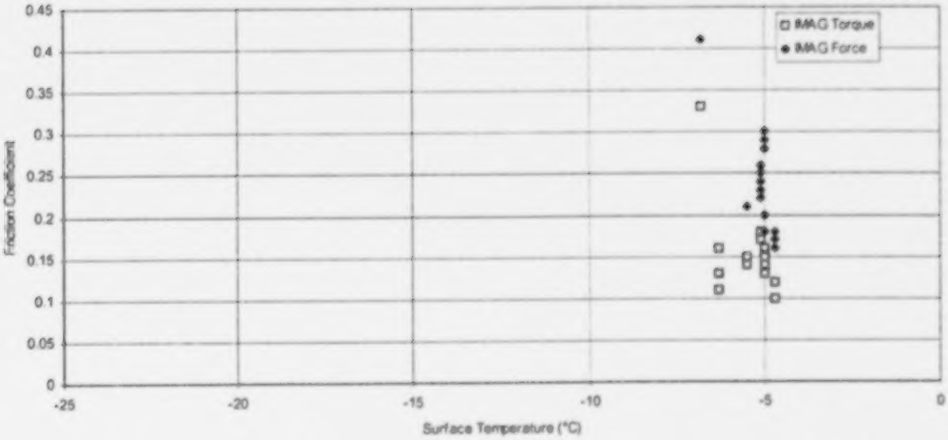
F.2-2: TC SFT'79 (All Configurations) Readings for Snow on a Packed Snow Base: Effect of Surface Temperature



F.2-3: TC SFT'79 (Configuration 3) Readings for Snow on a Packed Snow Base: Effect of Surface Temperature



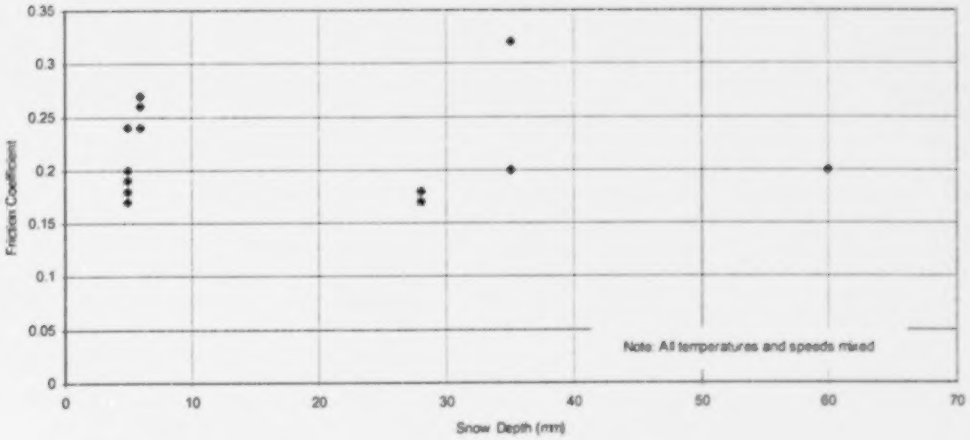
F.2-4: Effect of Temperature: IMAG (All Configurations) Readings for Snow on Packed Snow



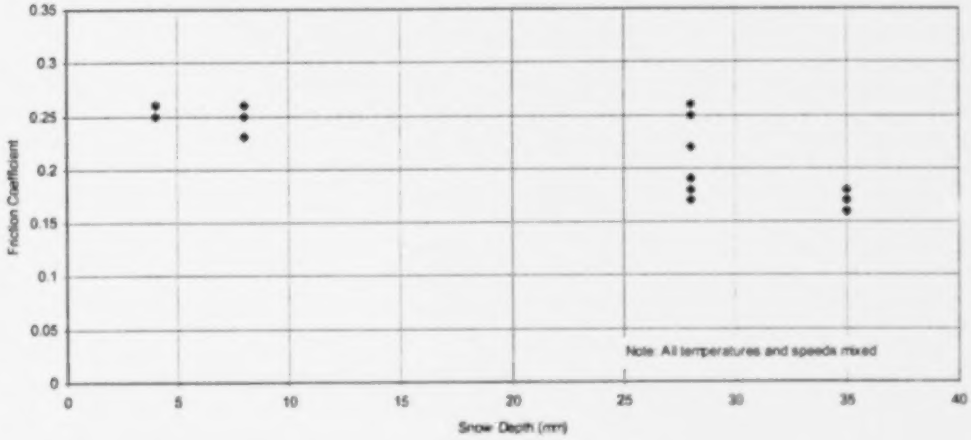
F.2-5: Effect of Temperature: IMAG (Configurations 3 and 7) Readings for Snow on Packed Snow

APPENDIX F.3

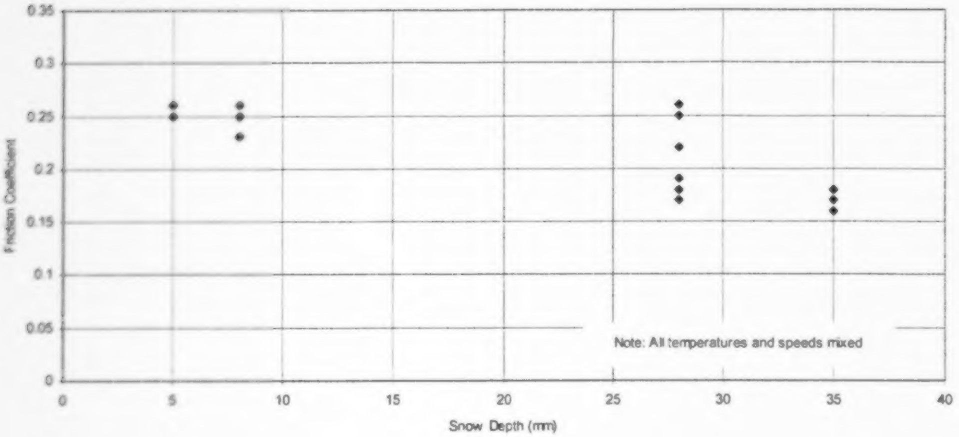
TREND PLOTS VS. SNOW DEPTH (ALL SNOW DEPTHS)



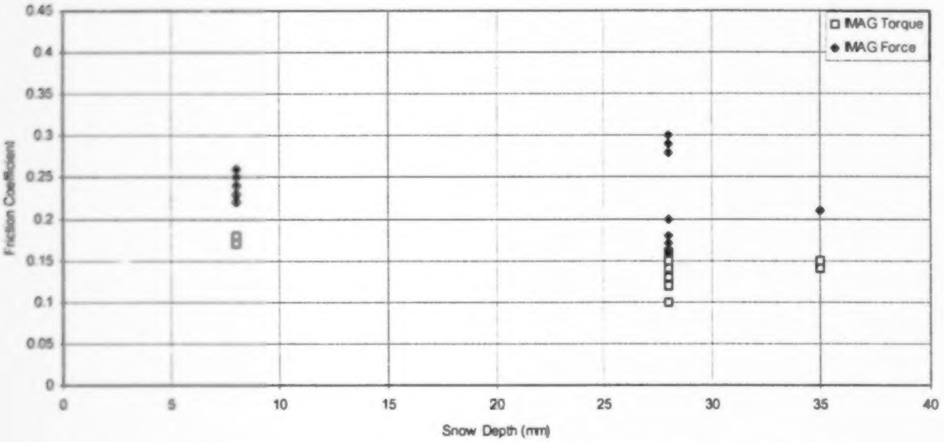
F.3-1: ERD Readings for Snow on a Packed Snow Base: Effect of Snow Depth



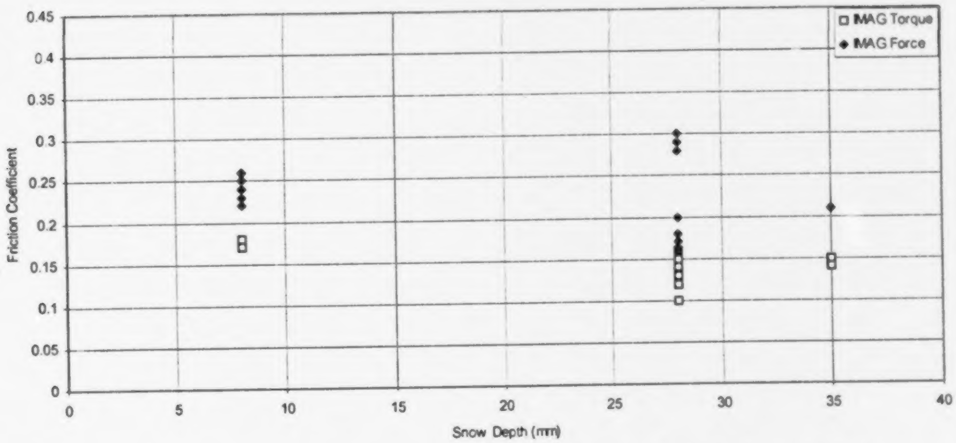
F.3-2: TC SFT'79 (All Configurations) Readings for Snow on a Packed Snow Base: Effect of Snow Depth



F.3-3: TC SFT'79 (Configuration 3) Readings for Snow on a Packed Snow Base: Effect of Snow Depth



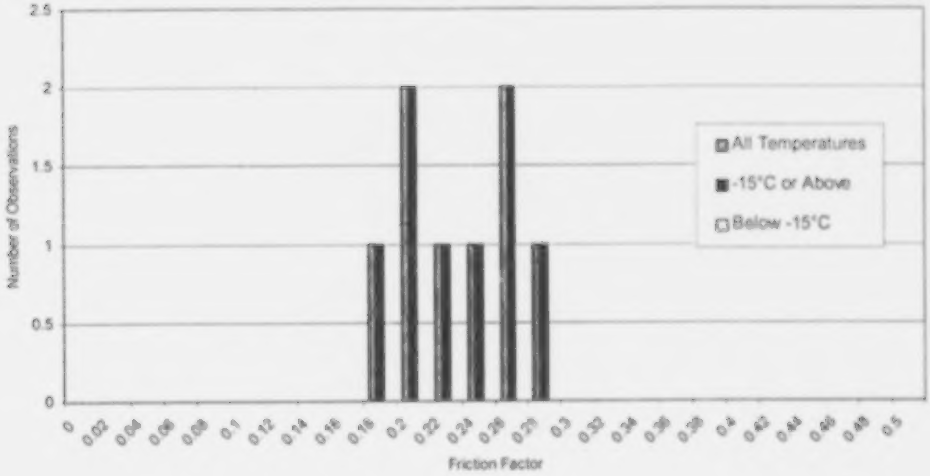
F.3-4: Effect of Snow Depth: IMAG (All Configurations) Readings for Snow on Packed Snow



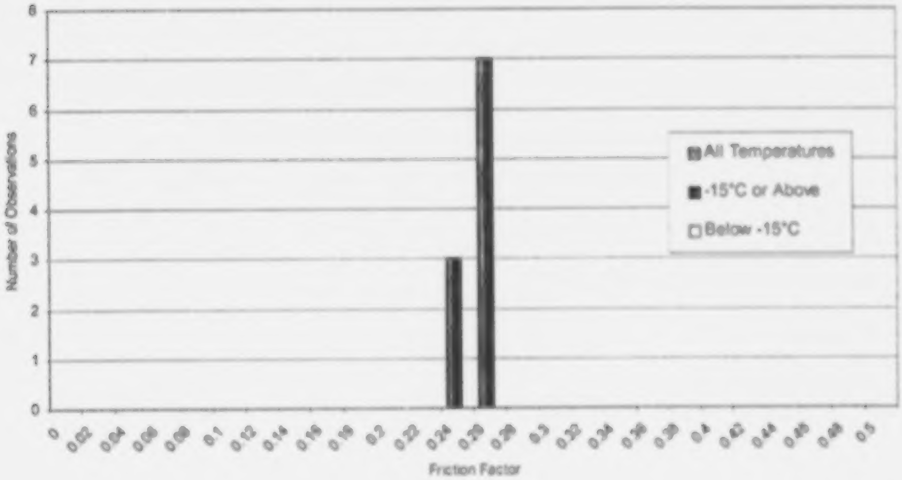
F.3-5: Effect of Snow Depth: IMAG (Configurations 3 and 7) Readings for Snow on Packed Snow

APPENDIX F.4

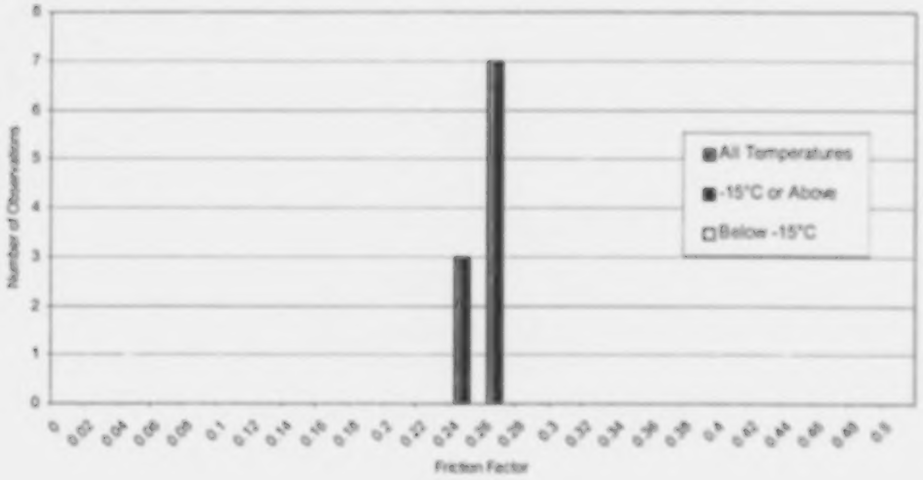
HISTOGRAMS FOR SNOW ON PACKED SNOW (SNOW DEPTHS 10 MM OR LESS)



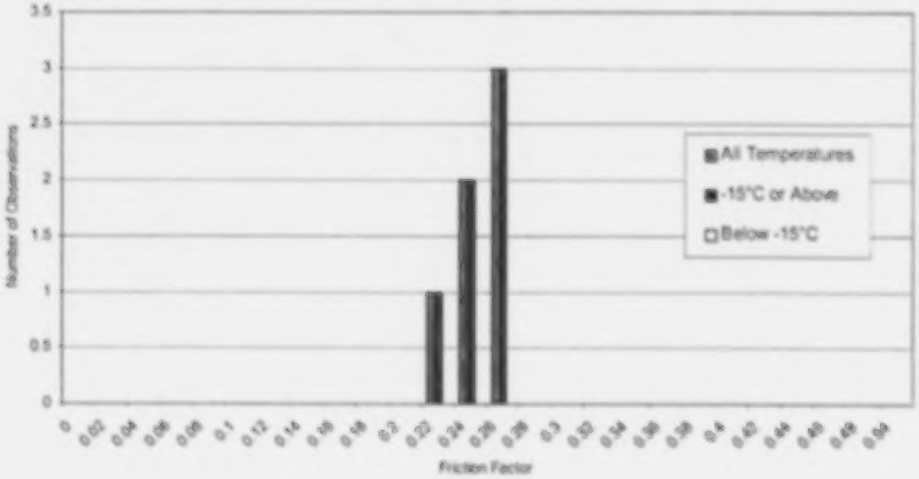
F.4-1: ERD Readings for Snow on a Packed Snow Base: Effect of Temperature



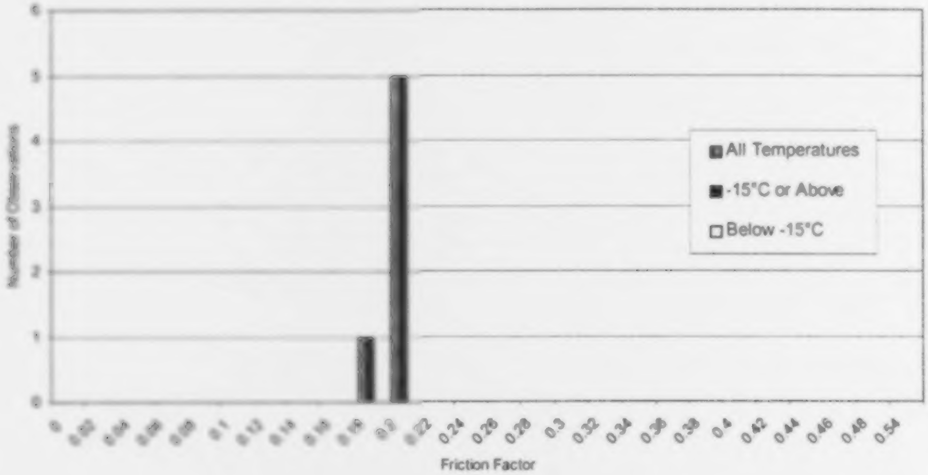
F.4-2: TC SFT'79 (All Configurations) Readings for Snow on a Packed Snow Base: Effect of Temperature



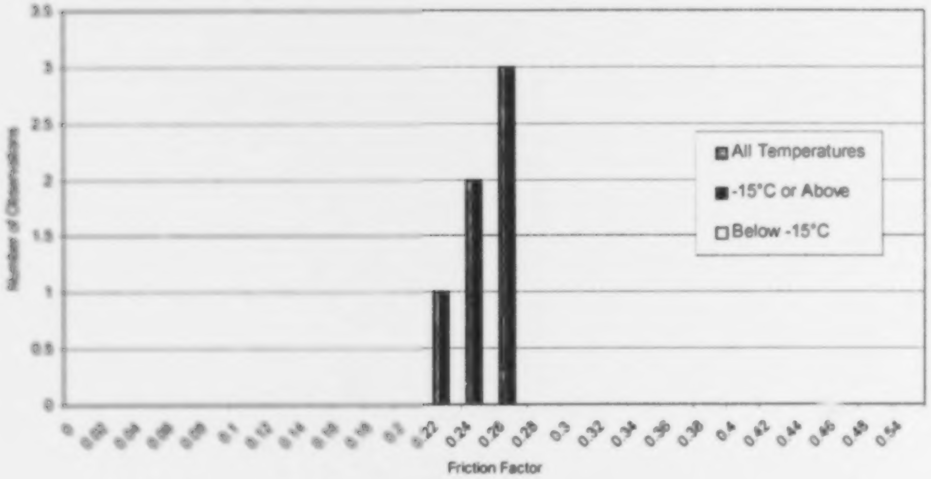
F.4-3: TC SFT'79 (Configuration 3) Readings for Snow on a Packed Snow Base: Effect of Temperature



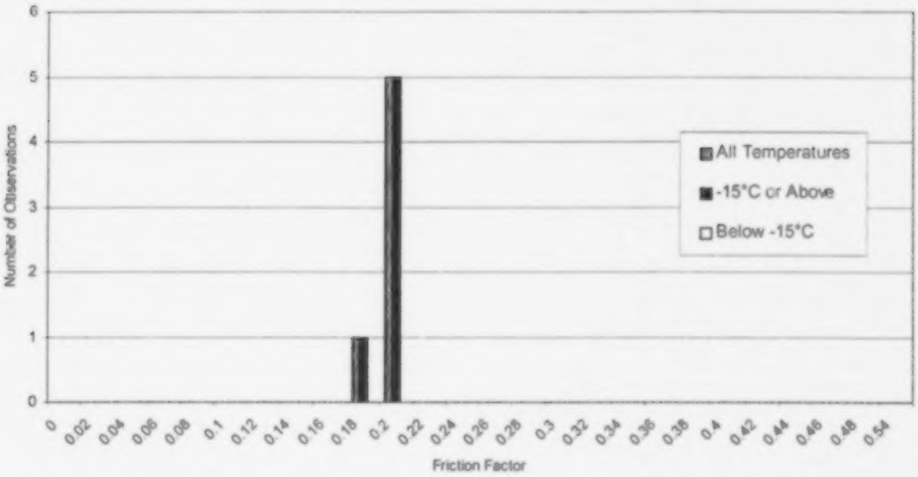
F.4-4: IMAG Force (All Configurations) Readings for Snow on Packed Snow: Effect of Temperature



F.4-5: IMAG Torque (All Configurations) Readings for Snow on Packed Snow: Effect of Temperature



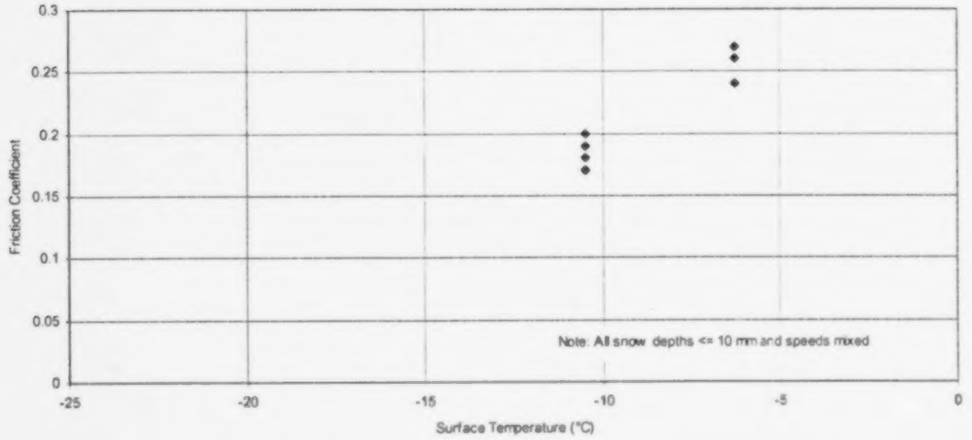
F.4-6: IMAG Force (Configurations 3 and 7) Readings for Snow on Packed Snow: Effect of Temperature



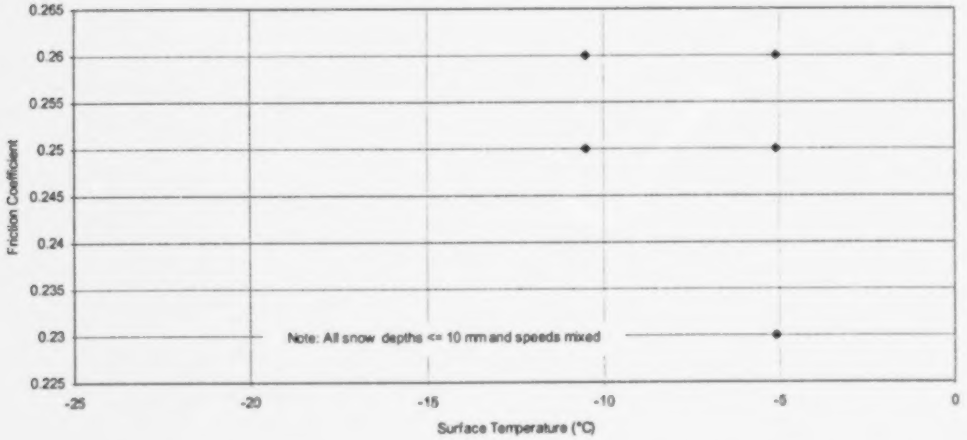
F.4-7: IMAG Torque (Configurations 3 and 7) Readings for Snow on a Packed Snow: Effect of Temperature

APPENDIX F.5

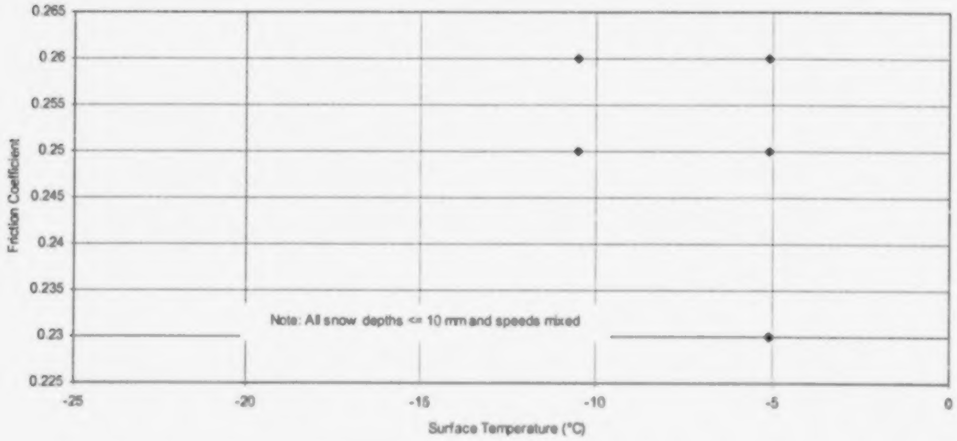
TREND PLOTS VS. SURFACE TEMPERATURE (SNOW DEPTHS 10 MM OR LESS)



F.5-1: ERD Readings for Snow on a Packed Snow Base: Effect of Surface Temperature

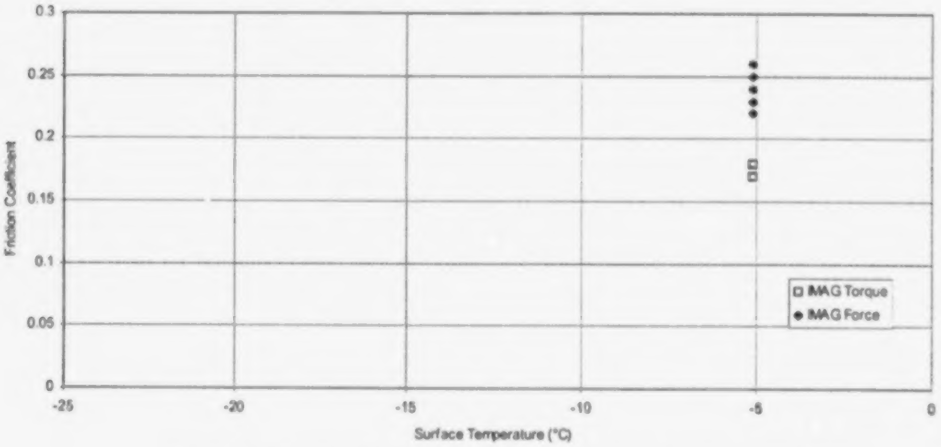


F.5-2: TC SFT'79 (All Configurations) Readings for Snow on a Packed Snow Base: Effect of Surface Temperature

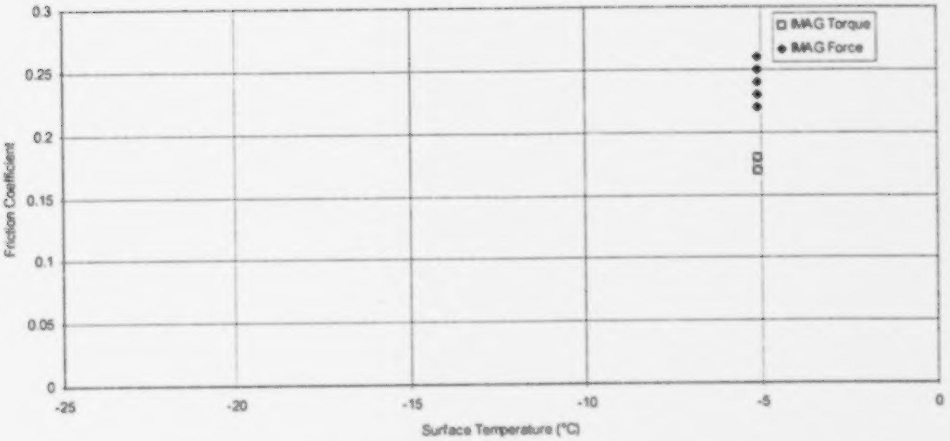


Note: All snow depths <= 10 mm and speeds mixed

F.5-3: TC SFT'79 (Configuration 3) Readings for Snow on a Packed Snow Base: Effect of Surface Temperature



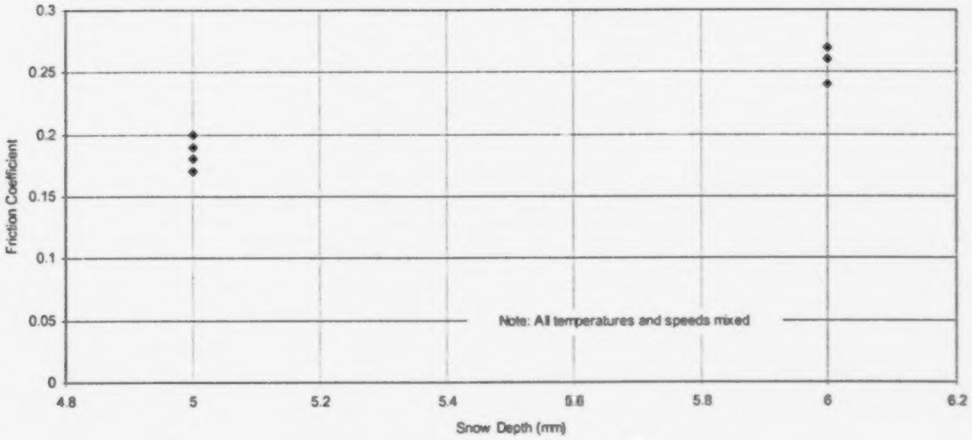
F.5-4: Effect of Temperature: IMAG (All Configurations) Readings for Snow on Packed Snow



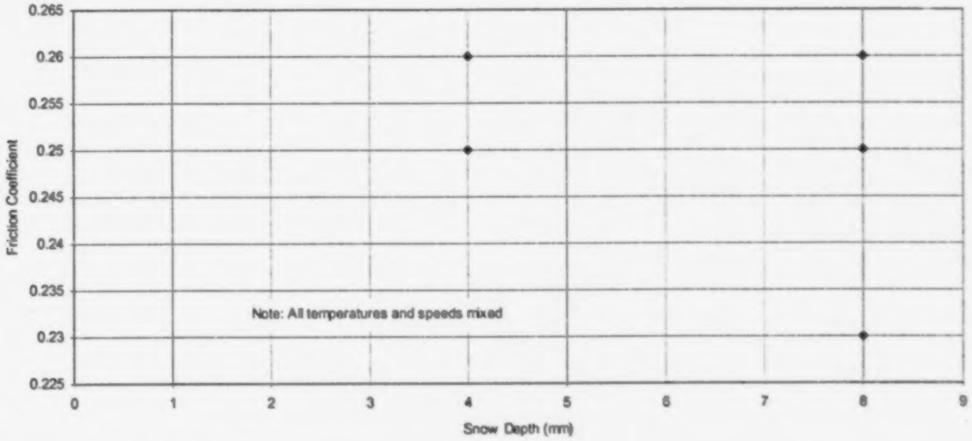
F.5-5: Effect of Temperature: IMAG (Configurations 3 and 7) Readings for Snow on Packed Snow

APPENDIX F.6

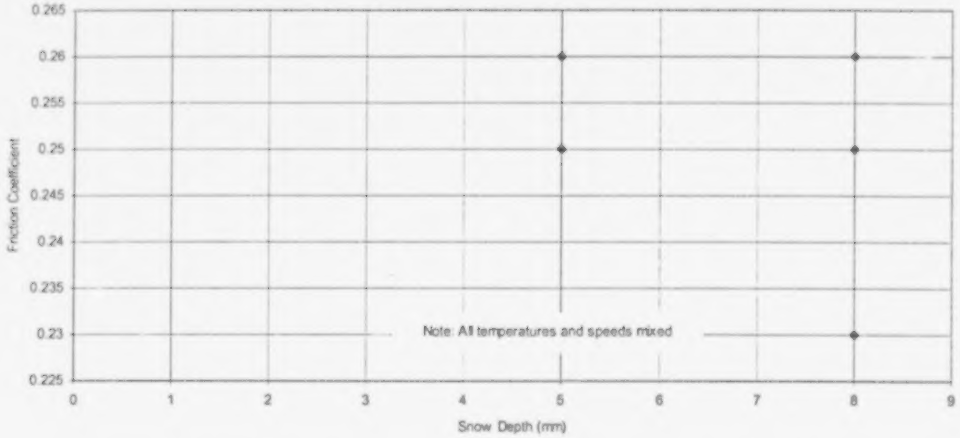
TREND PLOTS VS. SNOW DEPTH
(SNOW DEPTHS 10 MM OR LESS)



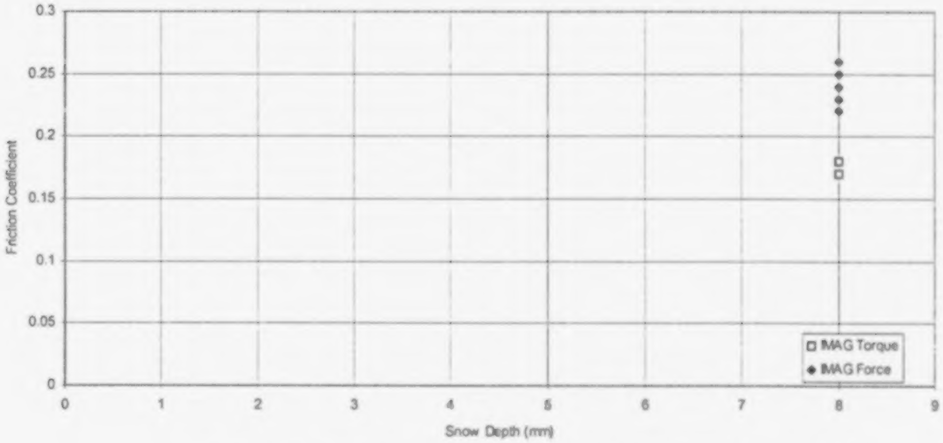
F.6-1: ERD Readings for Snow on a Packed Snow Base: Effect of Snow Depth



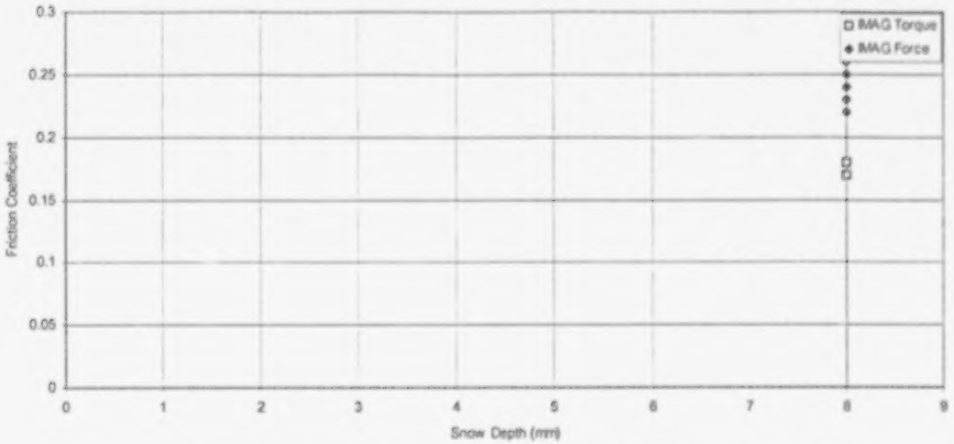
F.6-2: TC SFT'79 (All Configurations) Readings for Snow on a Packed Snow Base: Effect of Snow Depth



F.6-3: TC SFT'79 (Configuration 3) Readings for Snow on a Packed Snow Base: Effect of Snow Depth



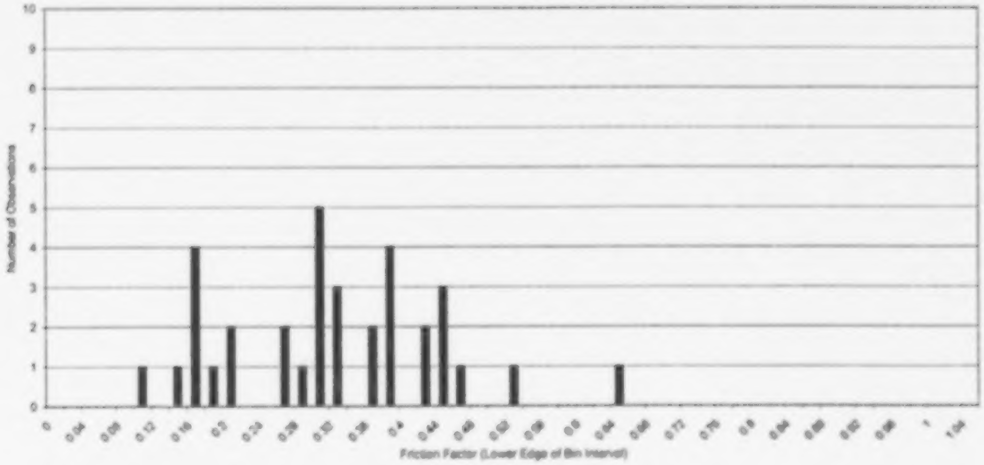
F.6-4: Effect of Snow Depth: IMAG (All Configurations) Readings for Snow on Packed Snow



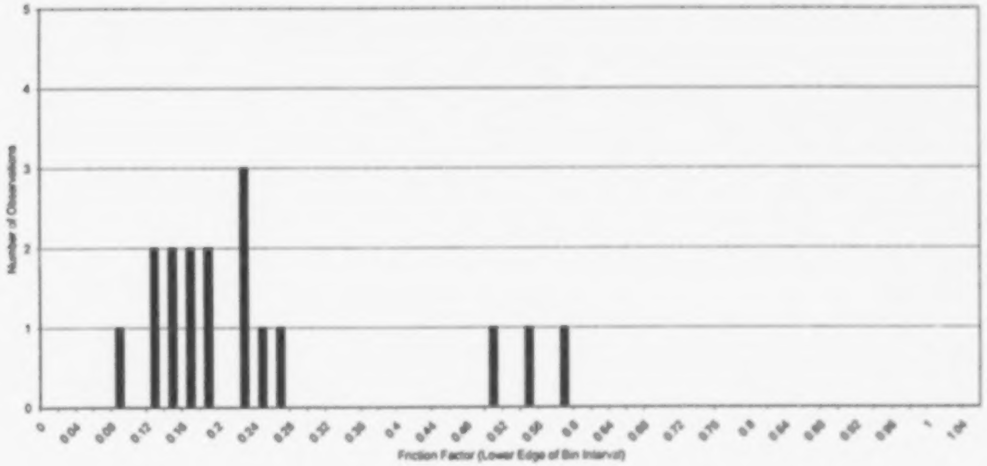
F.6-5: Effect of Snow Depth: IMAG (Configurations 3 and 7) Readings for Snow on Packed Snow

APPENDIX G

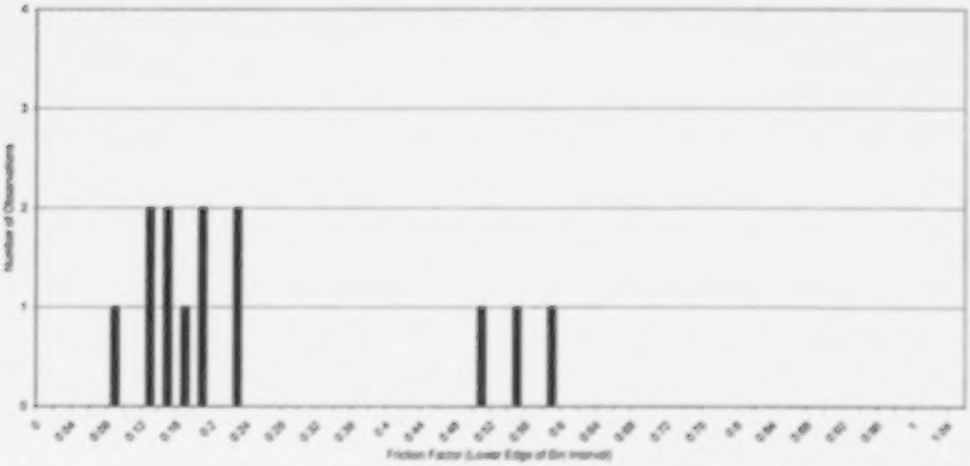
RESULTS FOR SLUSH ON ANY BASE SURFACE



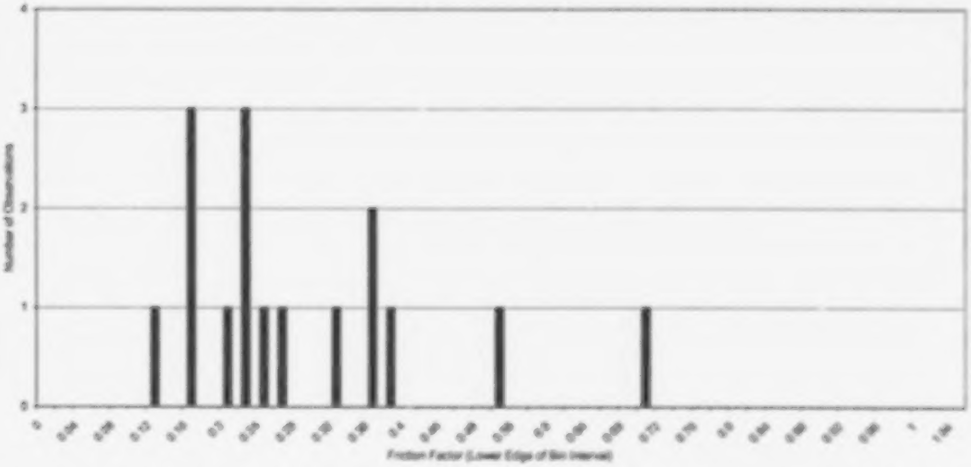
G-1: ERD Readings on Slush (on all bases): All Temperatures Included



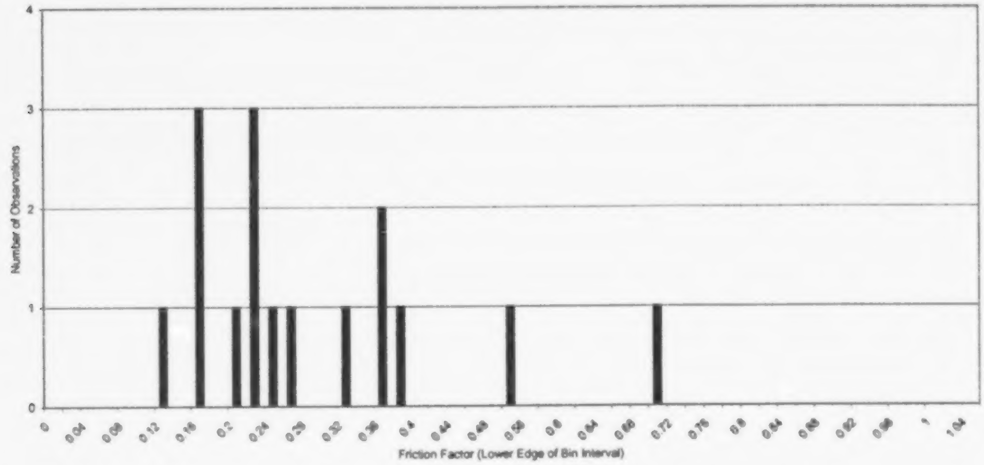
G-2: TC SFT'79 (All Configurations) Readings on Slush (on all bases): All Temperatures Included



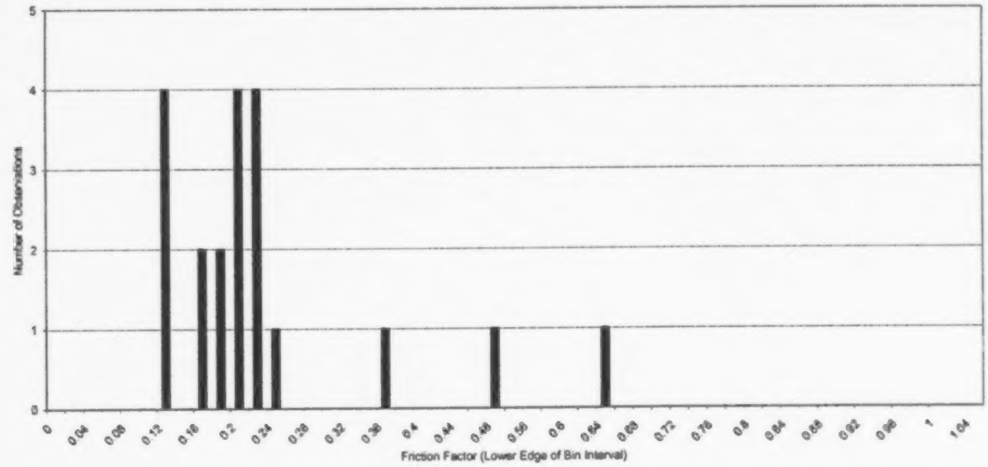
G-3: TC SFT'79 (Configuration 3) Readings on Slush (on all bases): All Temperatures Included



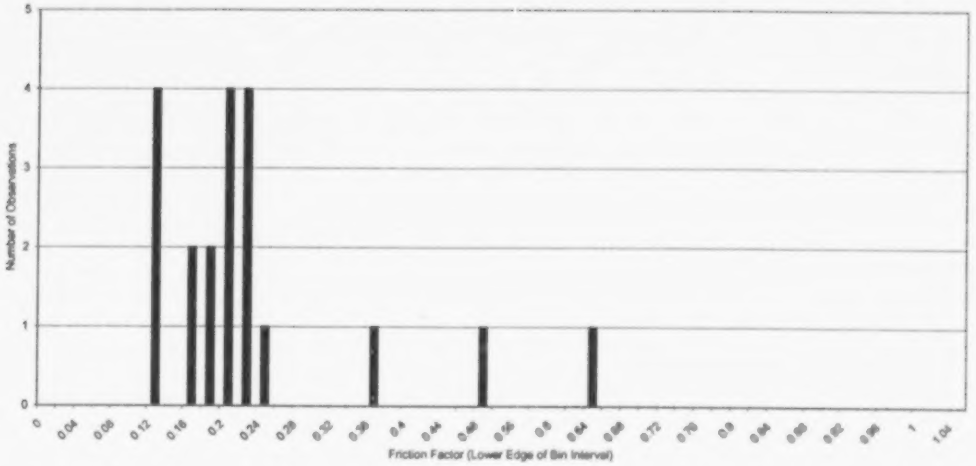
G-4: IMAG Force (All Configurations) Readings on Slush (on all bases): All Temperatures Included



G-5: IMAG Force (Configurations 3 and 7) Readings on Slush (on all bases): All Temperatures Included



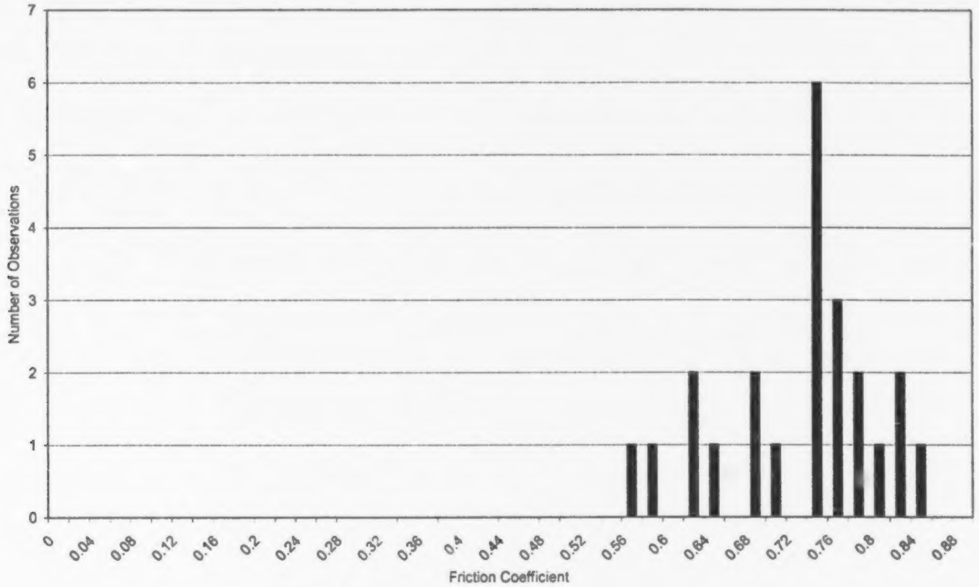
G-6: IMAG Torque (All Configurations) Readings on Slush (on all bases): All Temperatures Included



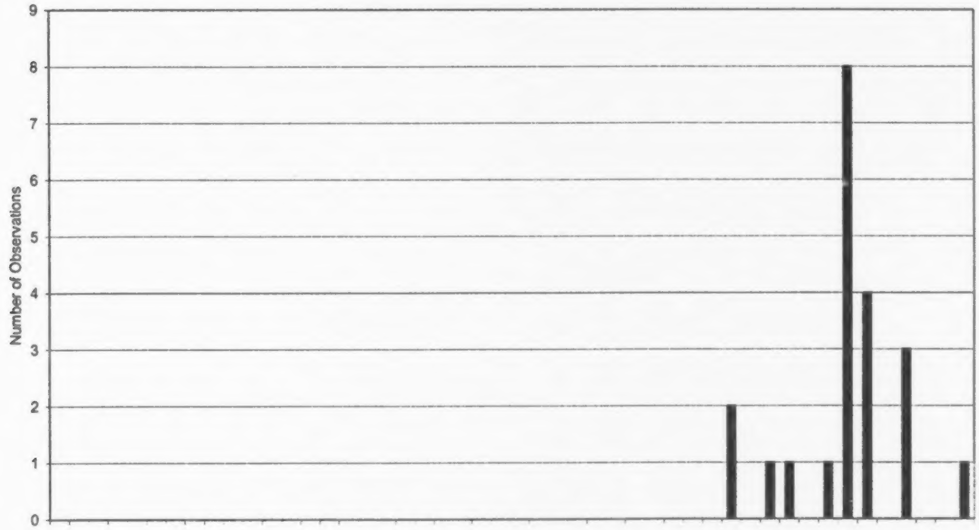
G-7: IMAG Torque (Configurations 3 and 7) Readings on Slush (on all bases): All Temperatures Included

APPENDIX H

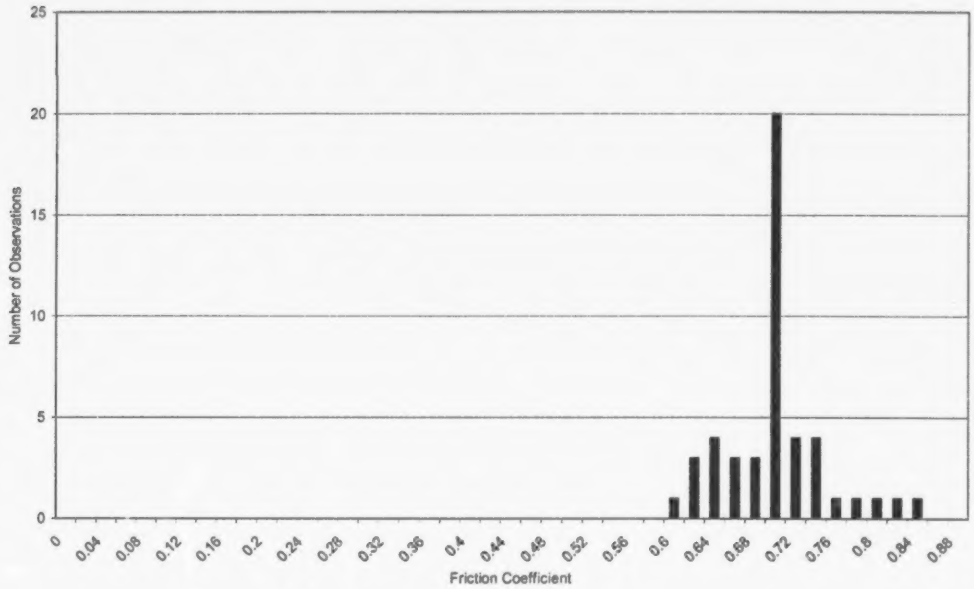
RESULTS FOR WET OR DAMP PAVEMENT



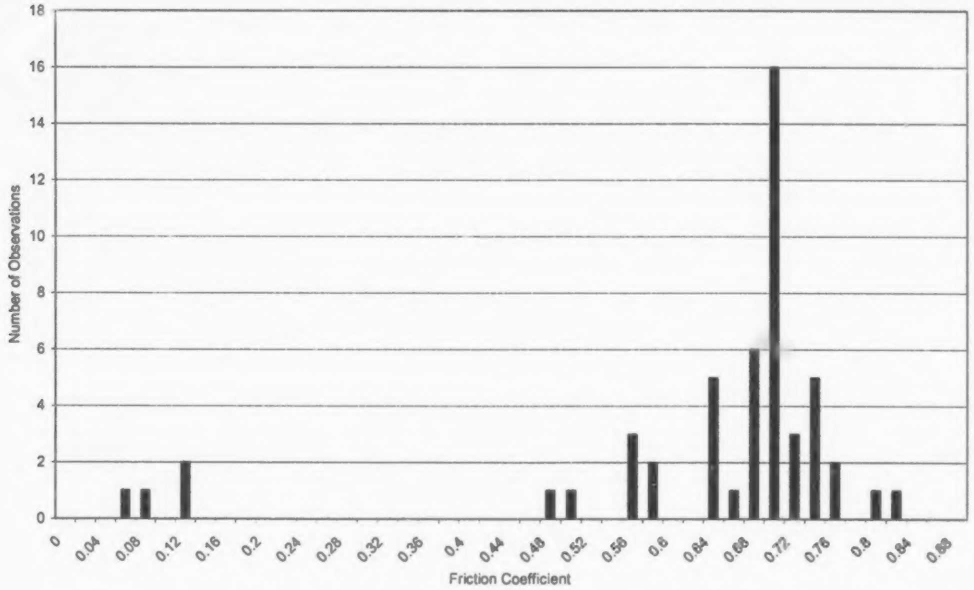
H-1: ERD Readings on Wet Pavement: All Speeds Combined



H-2: TC SFT'79 (Configuration 3) Readings on Wet Pavement: All Speeds Combined



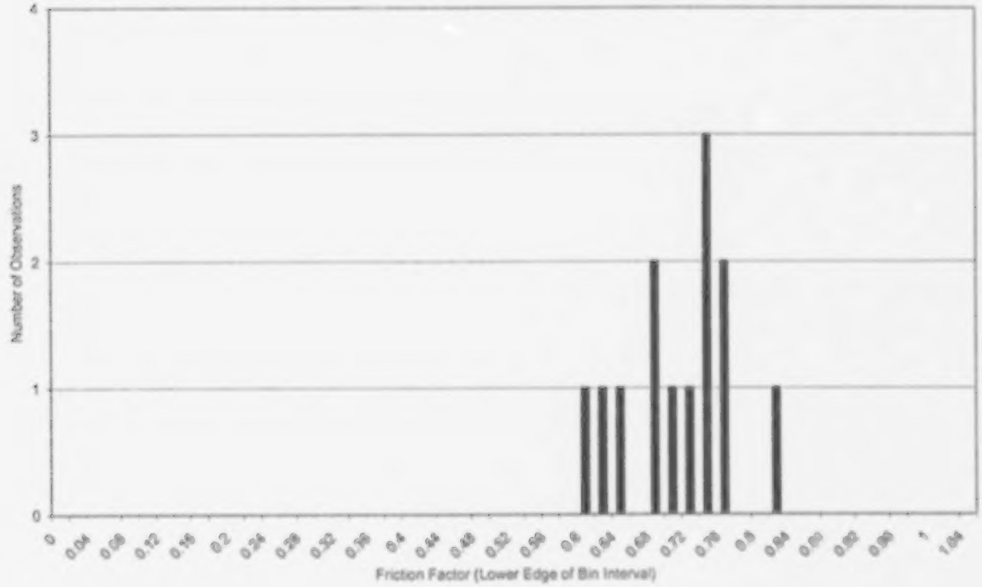
H-3: IMAG Force (Configurations 3 and 7) Readings on Wet Pavement: All Speeds Combined



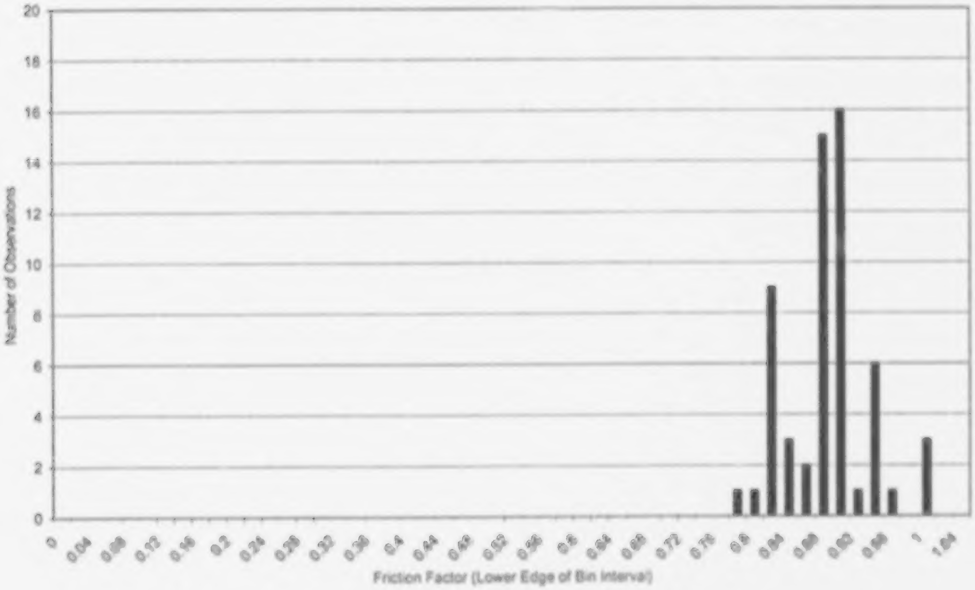
H-4: IMAG Torque (Configurations 3 and 7) Readings on Wet Pavement: All Speeds Combined

APPENDIX I

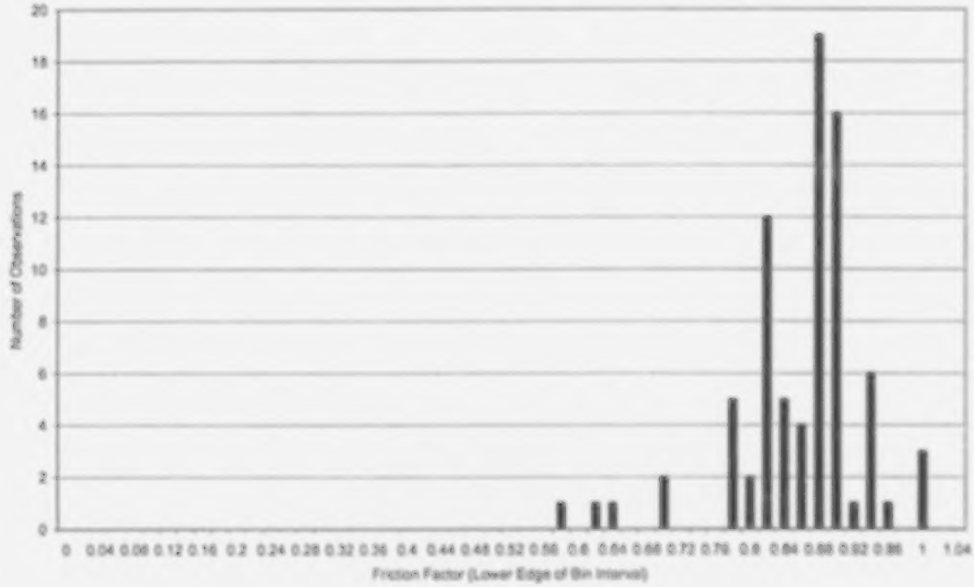
RESULTS FOR DRY PAVEMENT



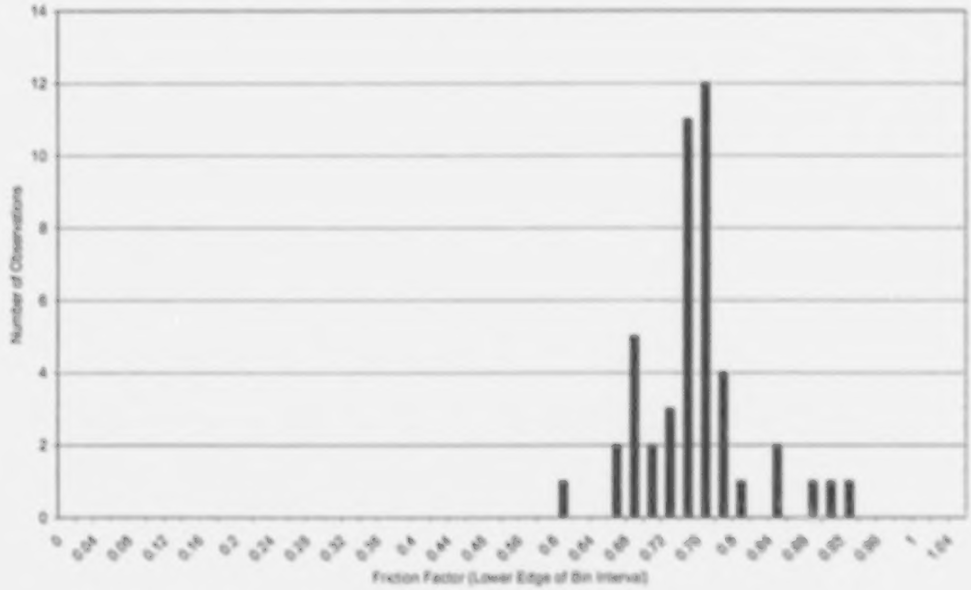
I-1: ERD Readings on Bare Pavement: All Temperatures Included



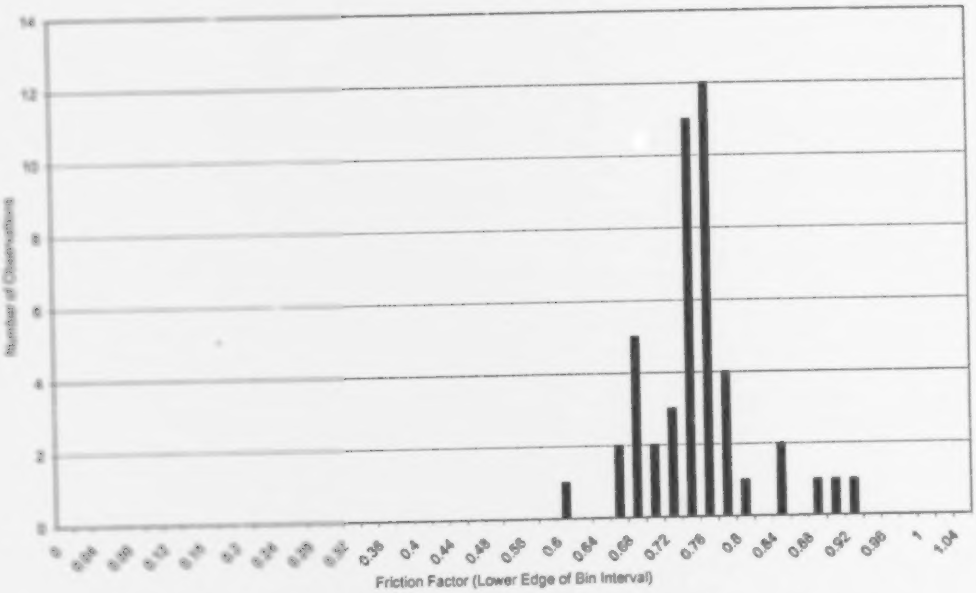
I-2: TC SFT'79 (All Configurations) Readings on Bare Pavement: All Temperatures Included



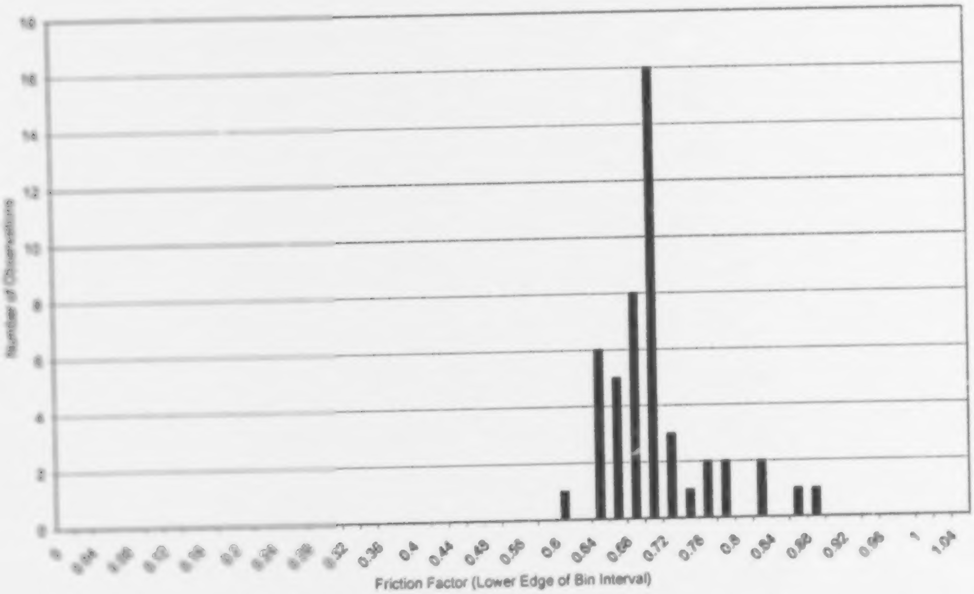
I-3: TC SFT'79 (Configuration 3) Readings on Bare Pavement:
All Temperatures Included



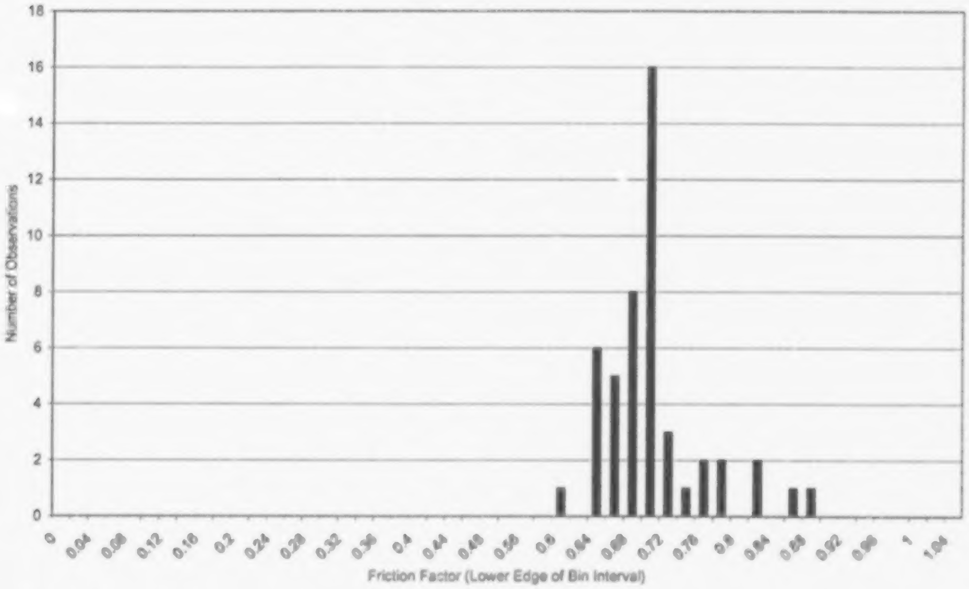
I-4: IMAG Force (All Configurations) Readings on Bare Pavement:
All Temperatures Included



I-5: IMAG Force (Configurations 3 and 7) Readings on Bare Pavement: All Temperatures Included



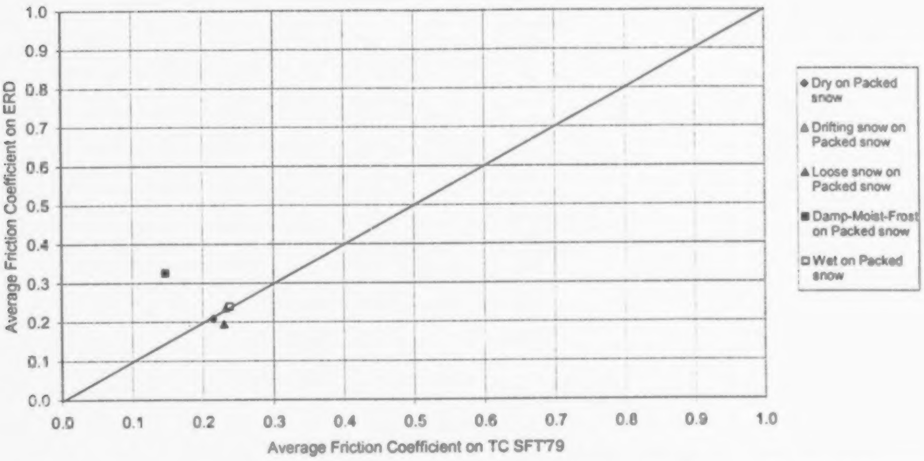
I-6: IMAG Torque (All Configurations) Readings on Bare Pavement: All Temperatures Included



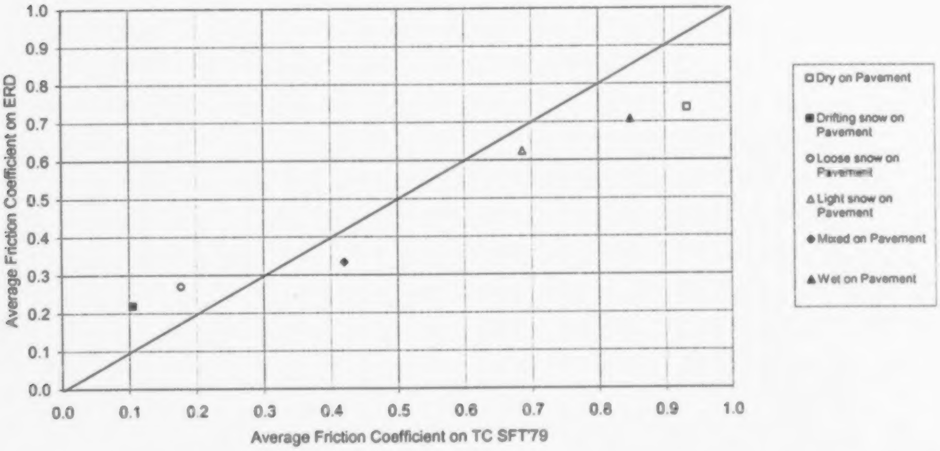
I-7: IMAG Torque (Configurations 3 and 7) Readings on Bare Pavement: All Temperatures Included

APPENDIX J

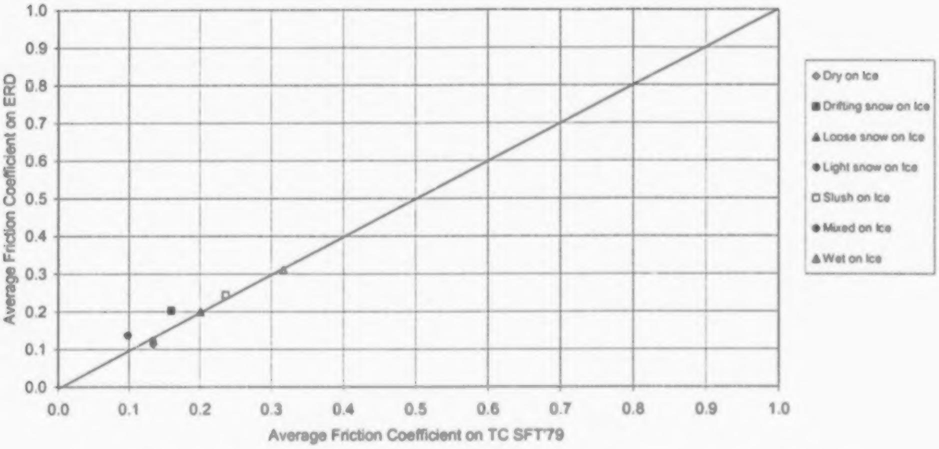
CORRELATION PLOTS: ERD VS. TC SFT'79



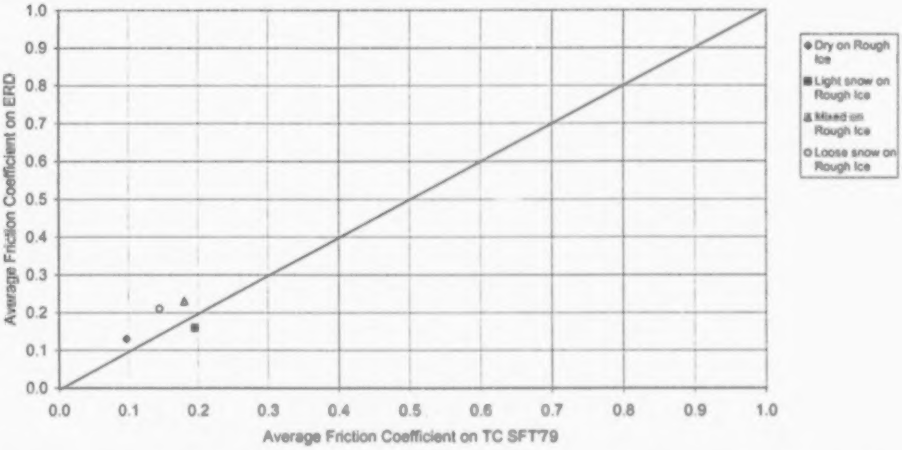
J-1: Correlation of ERD to TC SFT'79 (Configuration 3) on Packed Snow



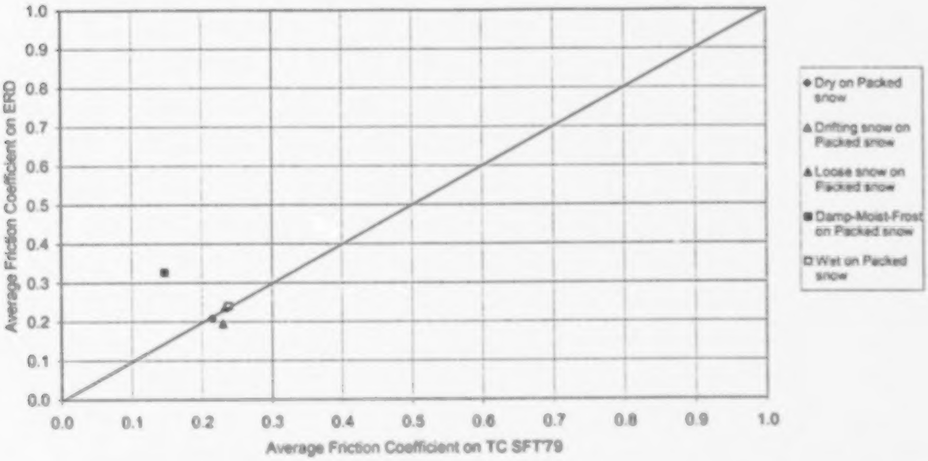
J-2: Correlation of ERD to TC SFT'79 (Configuration 3) on a Pavement Base



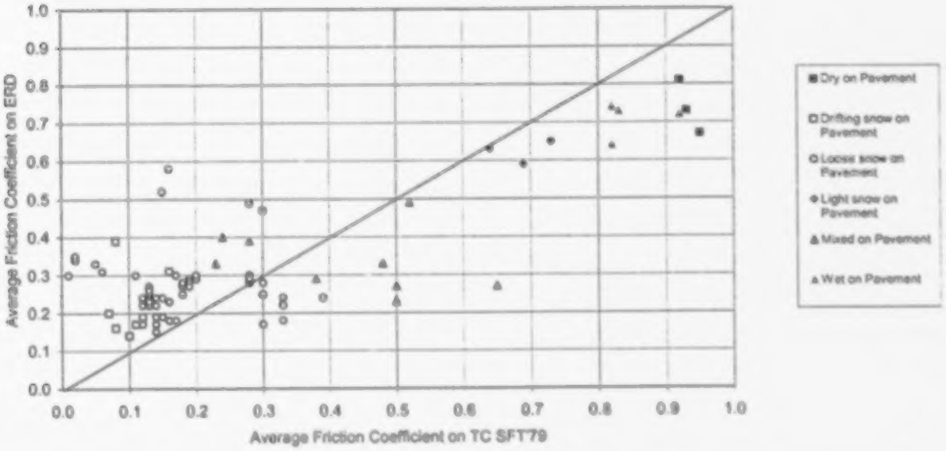
J-3: Correlation of ERD to TC SFT'79 (Configuration 3) on Ice Base



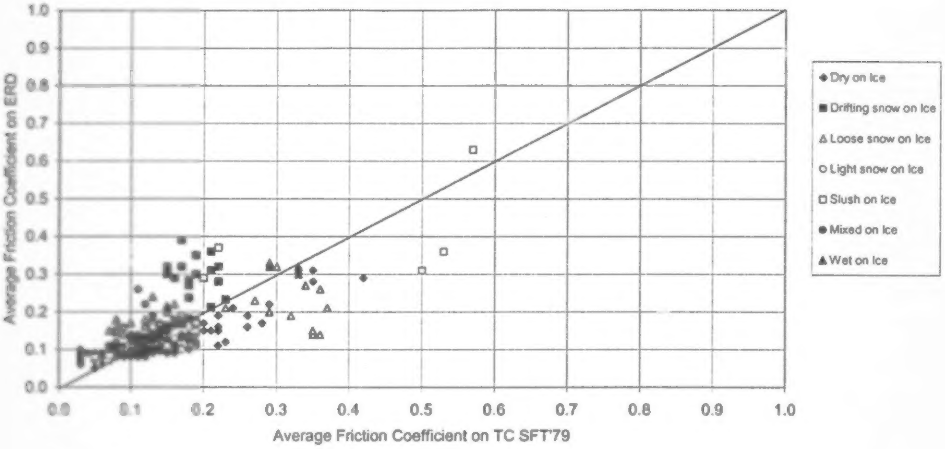
J-4: Correlation of ERD to TC SFT'79 (Configuration 3) on a Rough Ice Base



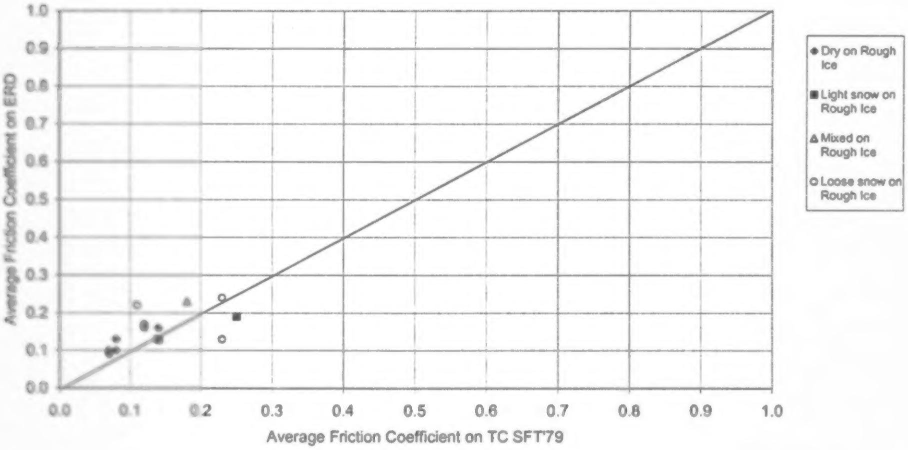
J-5: Correlation of ERD to TC SFT'79 (Configuration 3) on Packed Snow



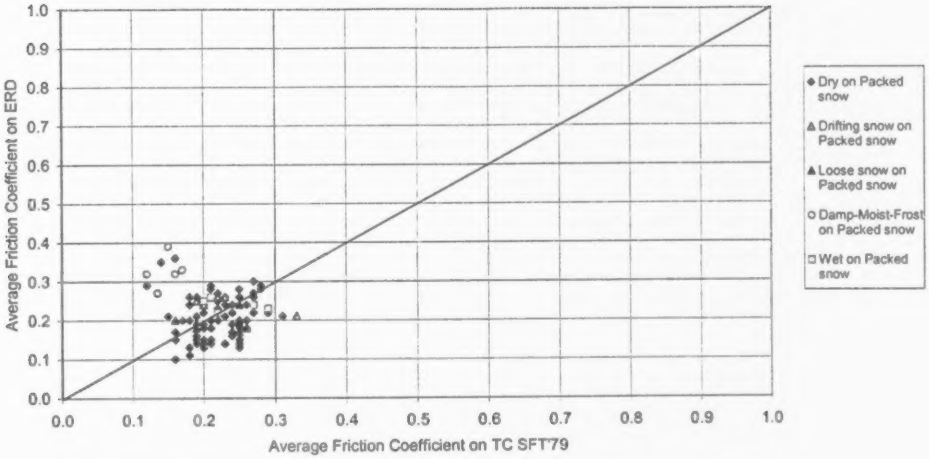
J-6: Correlation of ERD to TC SFT'79 (Configuration 3) on a Pavement Base



J-7: Correlation of ERD to TC SFT'79 (Configuration 3) on an Ice Base



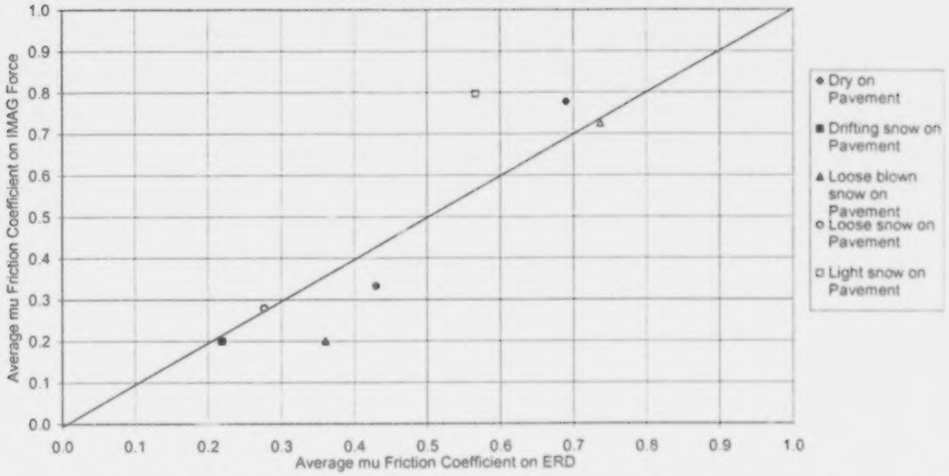
J-8: Correlation of ERD to TC SFT'79 (Configuration 3) on a Rough Ice Base



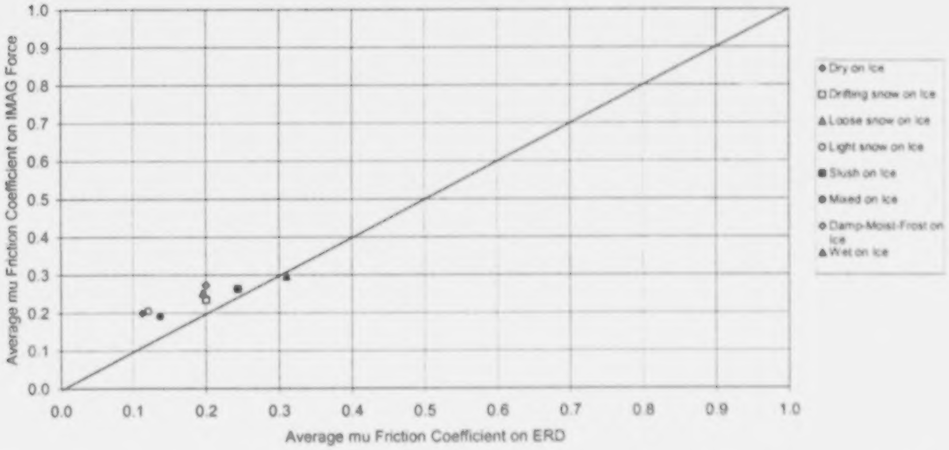
J-9: Correlation of ERD to TC SFT'79 (Configuration 3) on Packed Snow

APPENDIX K

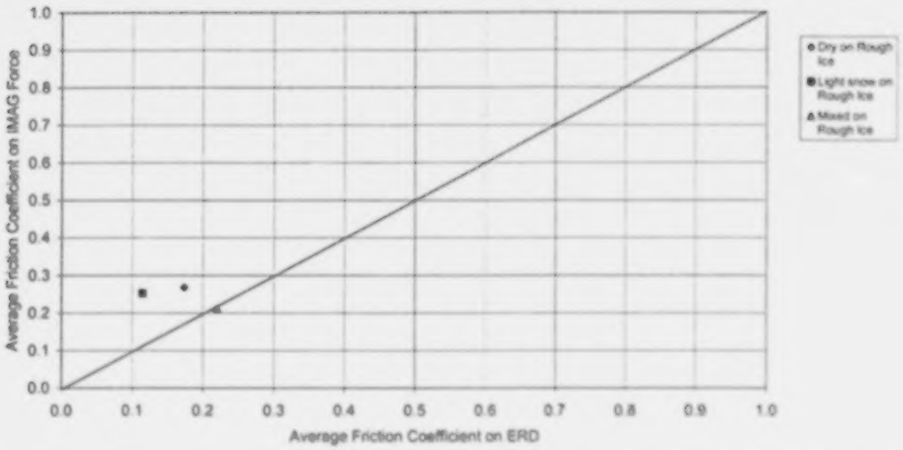
CORRELATION PLOTS: ERD VS. IMAG FORCE



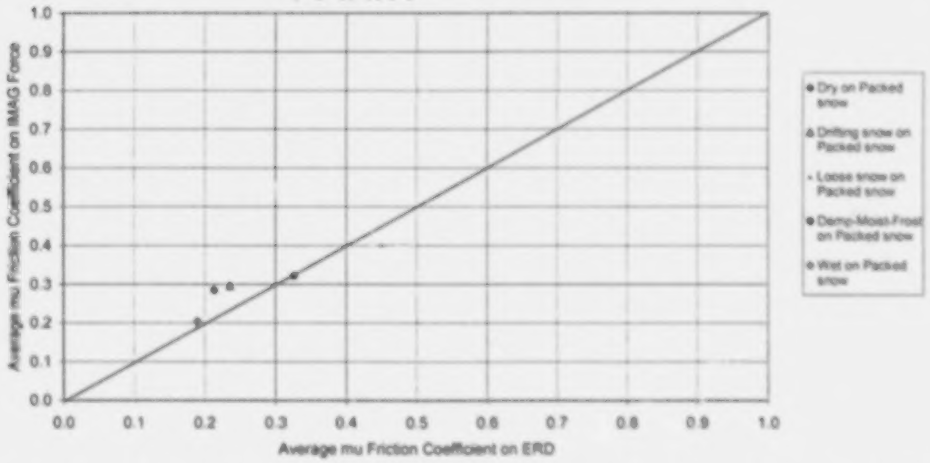
K-1: Correlation of ERD to IMAG Force (Configurations 3 and 7) on a Pavement Base



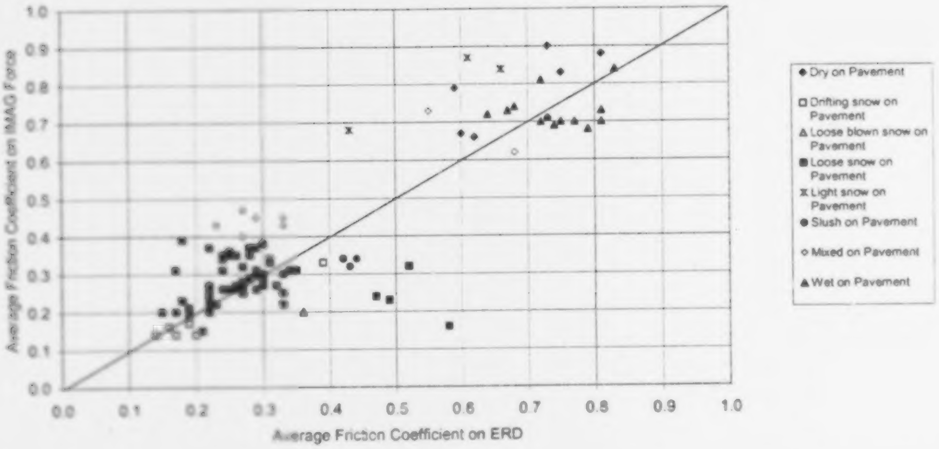
K-2: Correlation of ERD to IMAG Force (Configurations 3 and 7) on an Ice Base



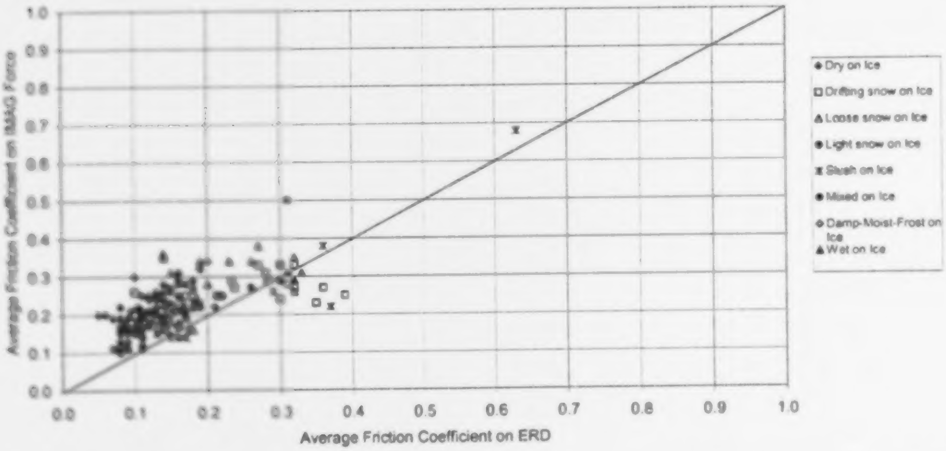
K-3: Correlation of ERD to IMAG Force (Configurations 3 and 7) on a Rough Ice Base



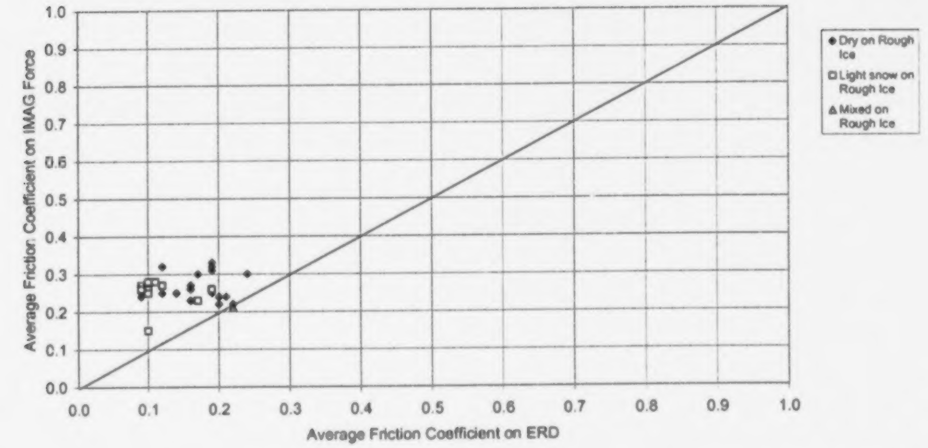
K-4: Correlation of ERD to IMAG Force (Configurations 3 and 7) on Packed Snow



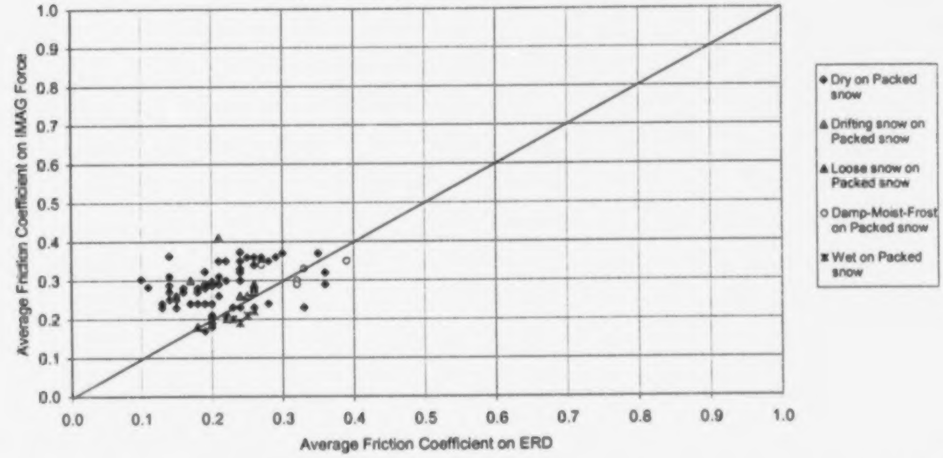
K-5: Correlation of ERD to IMAG Force (Configurations 3 and 7) on a Pavement Base



K-6: Correlation of ERD to IMAG Force (Configurations 3 and 7) on an Ice Base



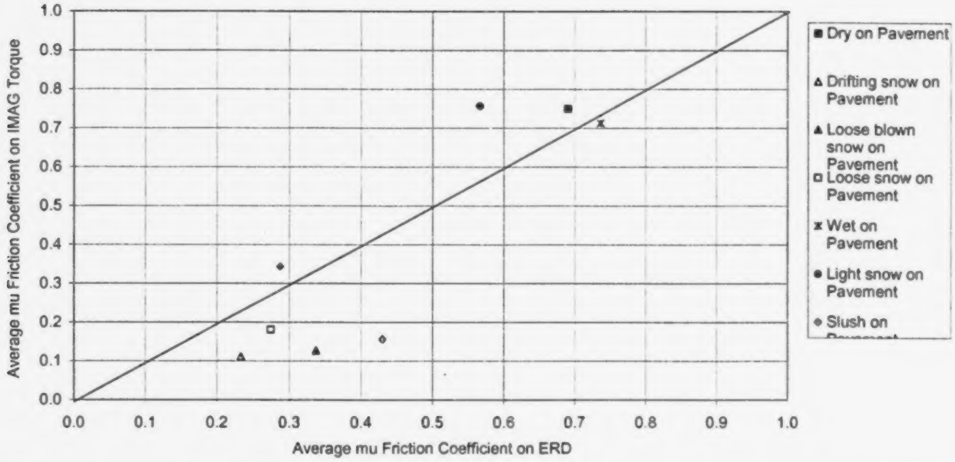
K-7: Correlation of ERD to IMAG Force (Configurations 3 and 7) on a Rough Ice Base



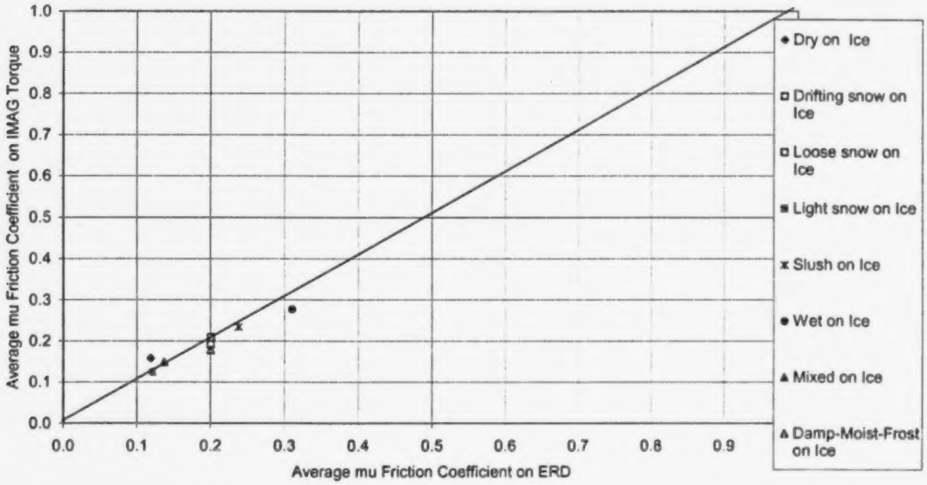
K-8: Correlation of ERD to IMAG Force (Configurations 3 and 7) on Packed Snow

APPENDIX L

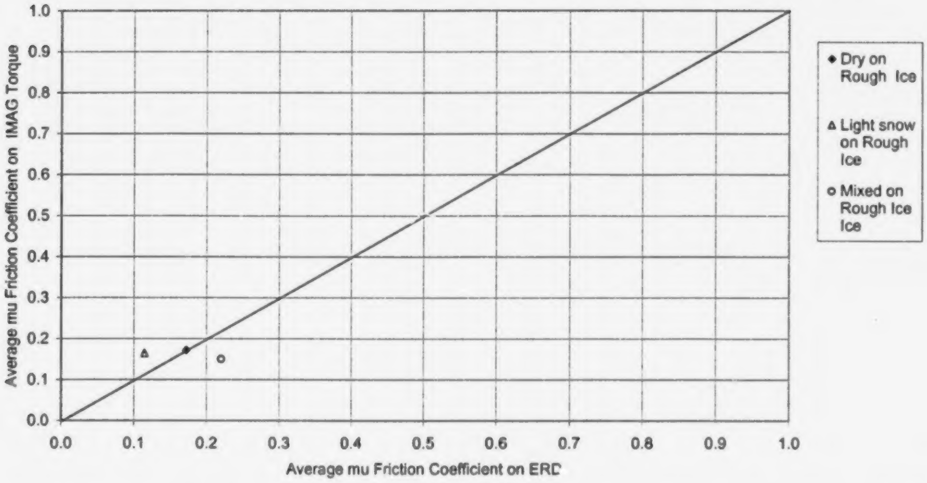
CORRELATION PLOTS: ERD VS. IMAG TORQUE



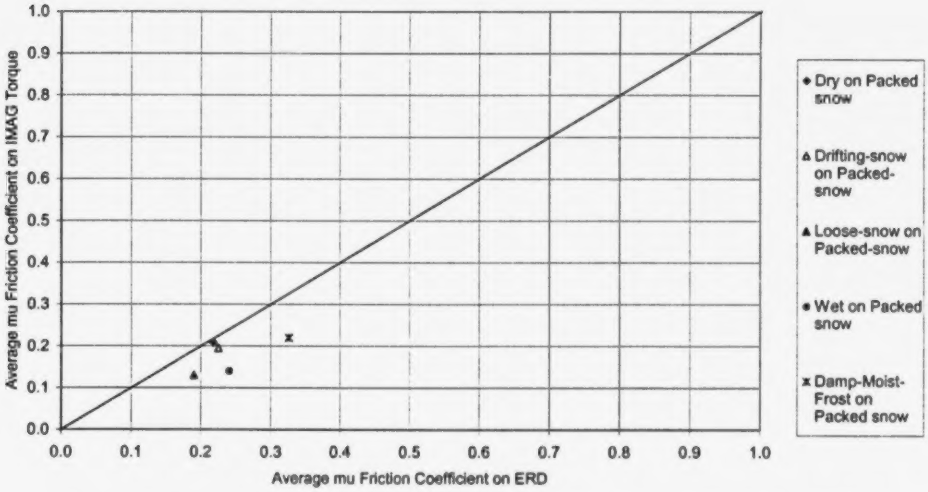
L-1: Correlation of ERD to IMAG Torque (Configurations 3 and 7) on a Pavement Base



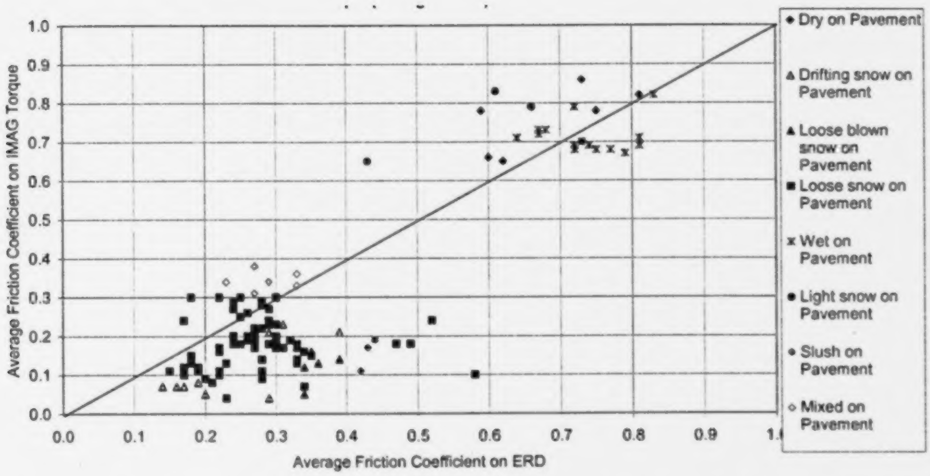
L-2: Correlation of ERD to IMAG Torque (Configurations 3 and 7) on an Ice Base



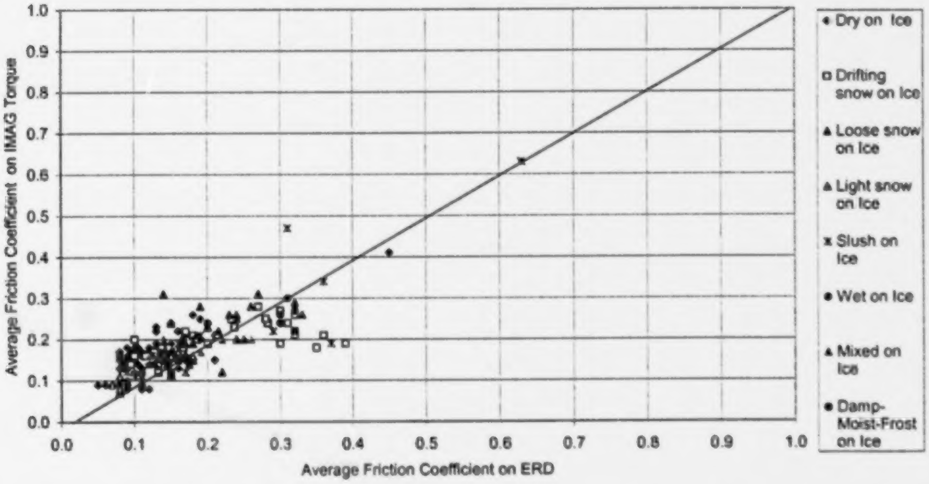
L-3: Correlation of ERD to IMAG Torque (Configurations 3 and 7) on a Rough Ice Base



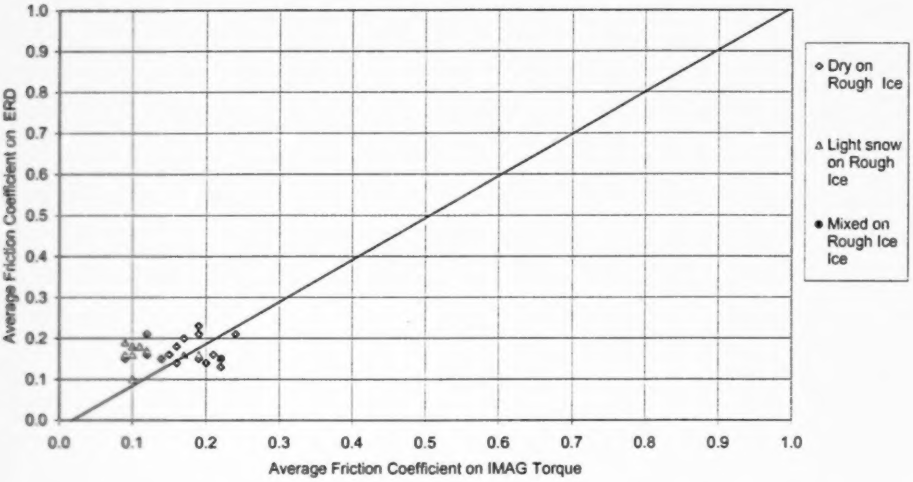
L-4: Correlation of ERD to IMAG Torque (Configurations 3 and 7) on a Packed Snow Base



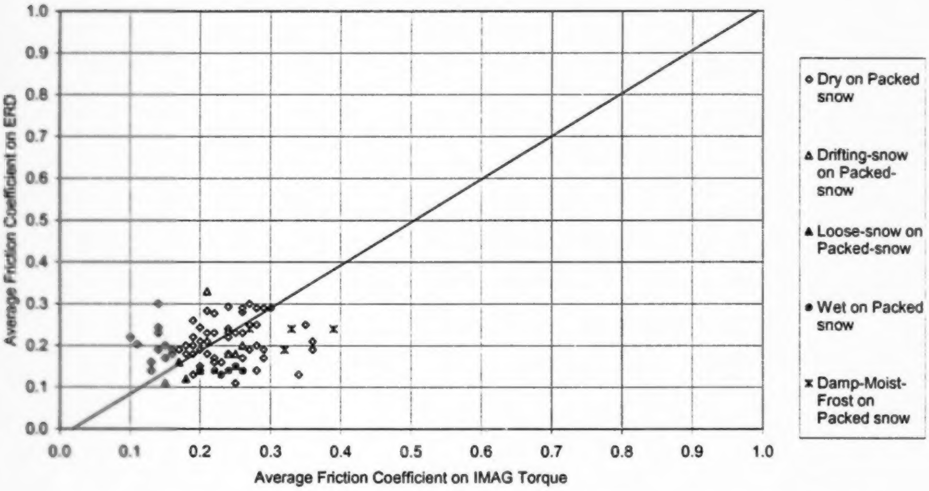
L-5: Correlation of ERD to IMAG Torque (Configurations 3 and 7) on a Pavement Base



L-6: Correlation of ERD to IMAG Torque (Configurations 3 and 7) on an Ice Base



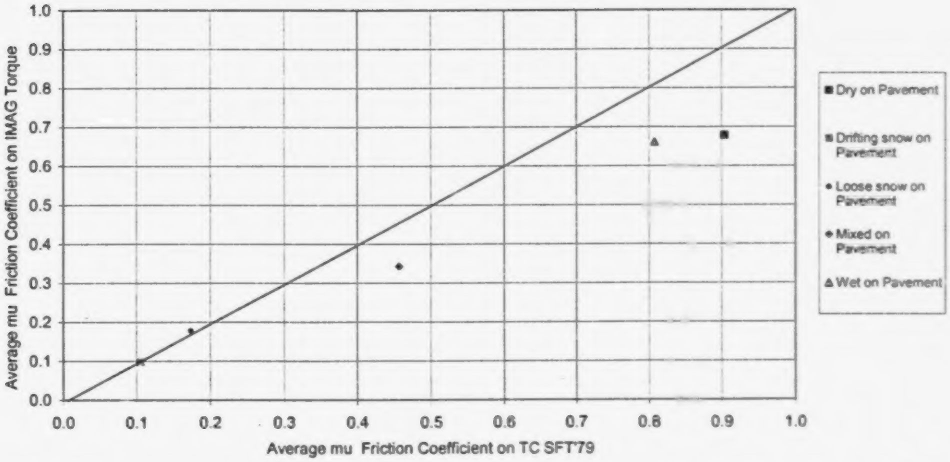
L-7: Correlation of ERD to IMAG Torque (Configurations 3 and 7) on a Rough Ice Base



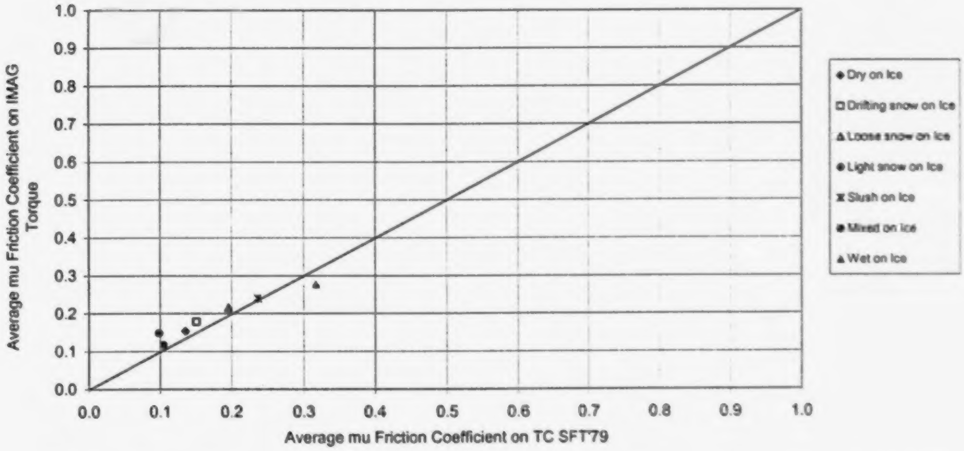
L-8: Correlation of ERD to IMAG Torque (Configurations 3 and 7) on a Packed Snow Base

APPENDIX M

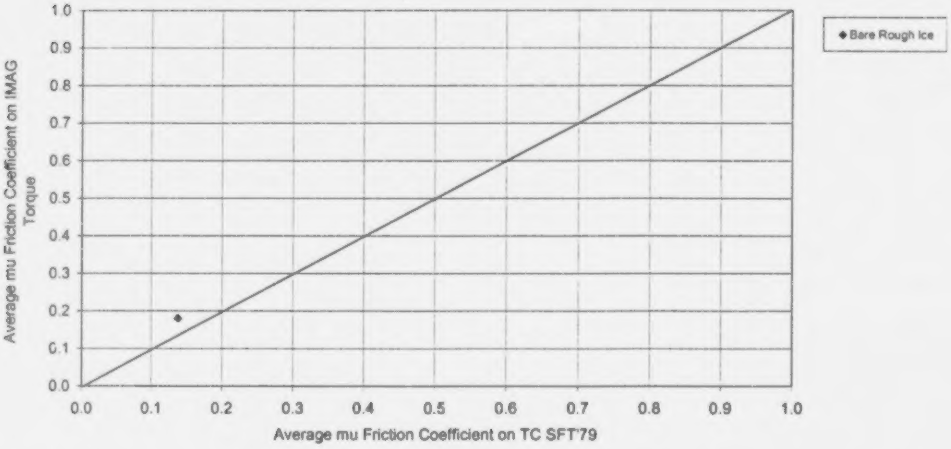
CORRELATION PLOTS: TC SFT'79 VS. IMAG TORQUE



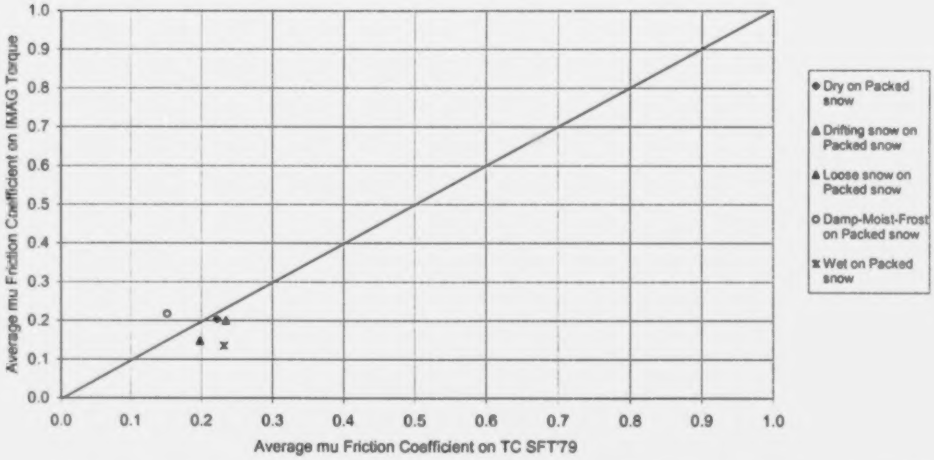
M-1: Correlation of TC SFT'79 to IMAG Torque (Configurations 3 and 7) on a Pavement Base



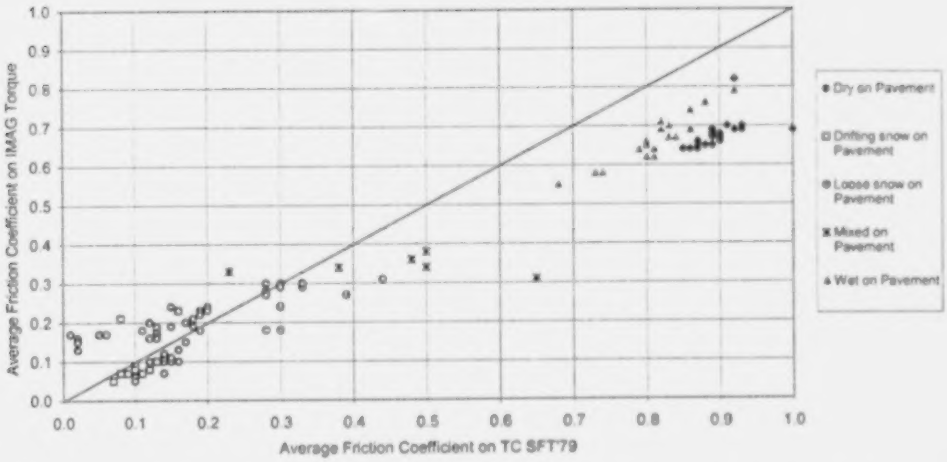
M-2: Correlation of TC SFT'79 to IMAG Torque (Configurations 3 and 7) on an Ice Base



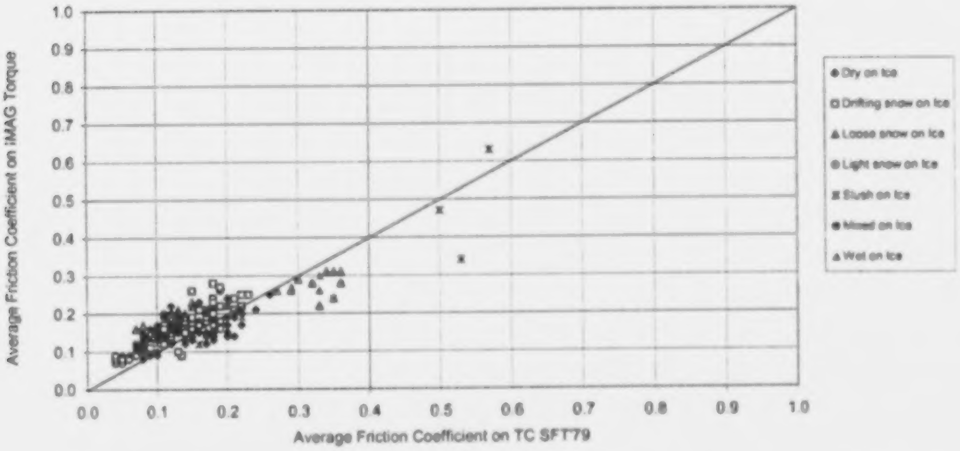
M-3: Correlation of TC SFT'79 to IMAG Torque (Configurations 3 and 7) on a Rough Ice Base



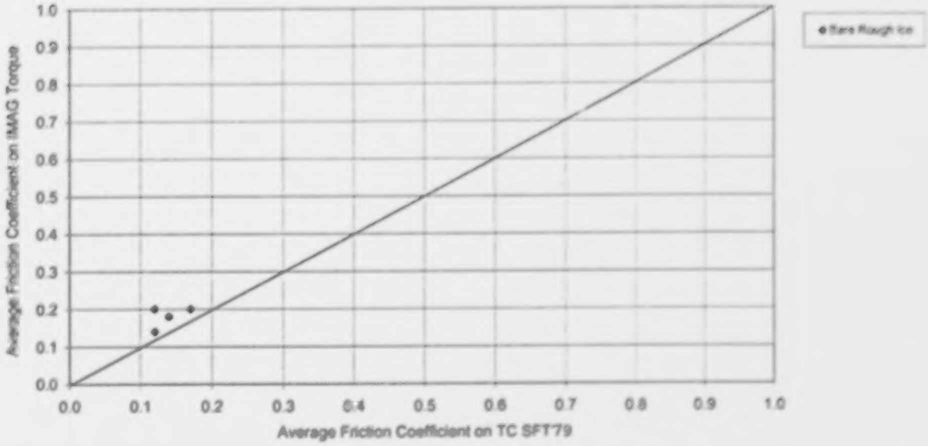
M-4: Correlation of TC SFT'79 to IMAG Torque (Configurations 3 and 7) on Packed Snow



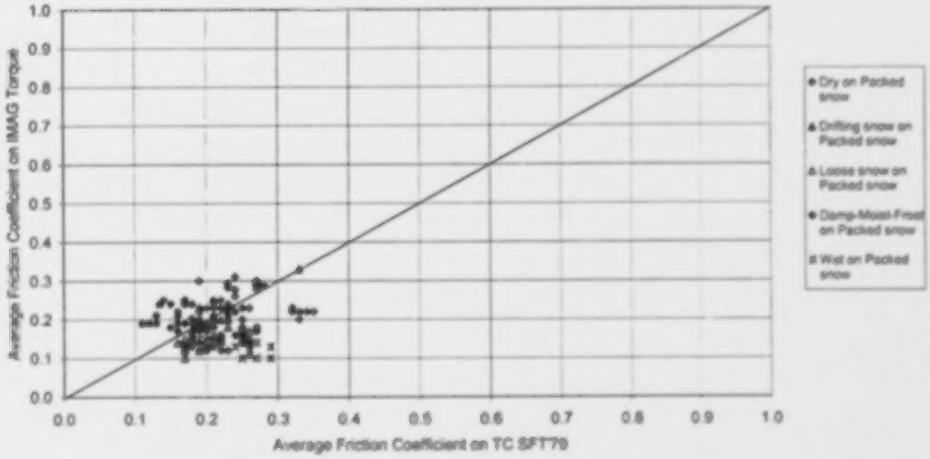
M-5: Correlation of TC SFT'79 to IMAG Torque (Configurations 3 and 7) on a Pavement Base



M-6: Correlation of TC SFT'79 to IMAG Torque (Configurations 3 and 7) on an Ice Base



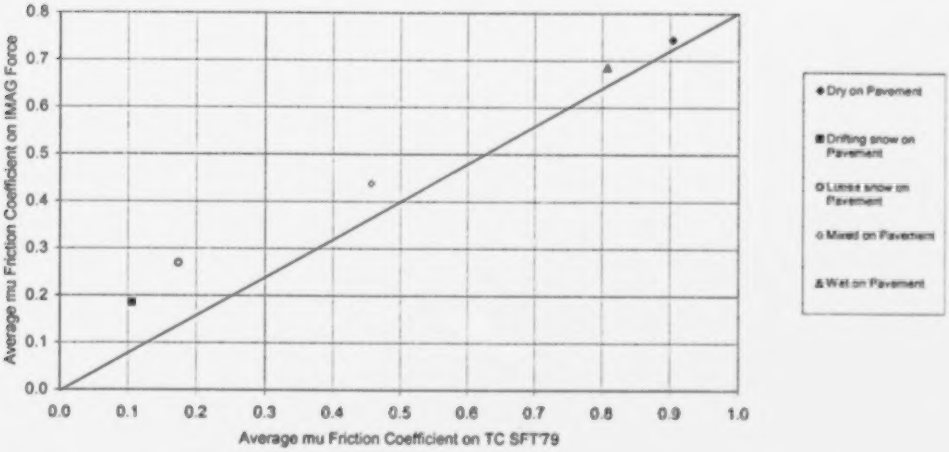
M-7: Correlation of TC SFT'79 to IMAG Torque (Configurations 3 and 7) on a Rough Ice Base



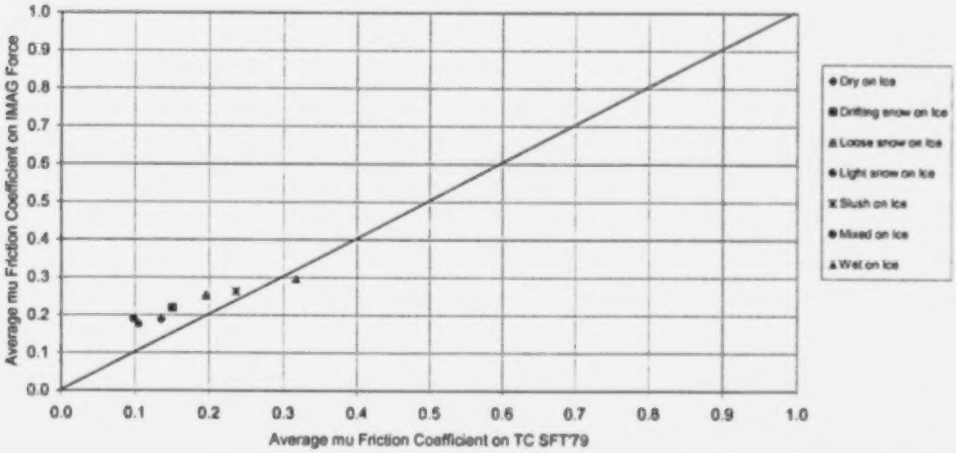
M-8: Correlation of TC SFT'79 to IMAG Torque (Configurations 3 and 7) on Packed Snow

APPENDIX N

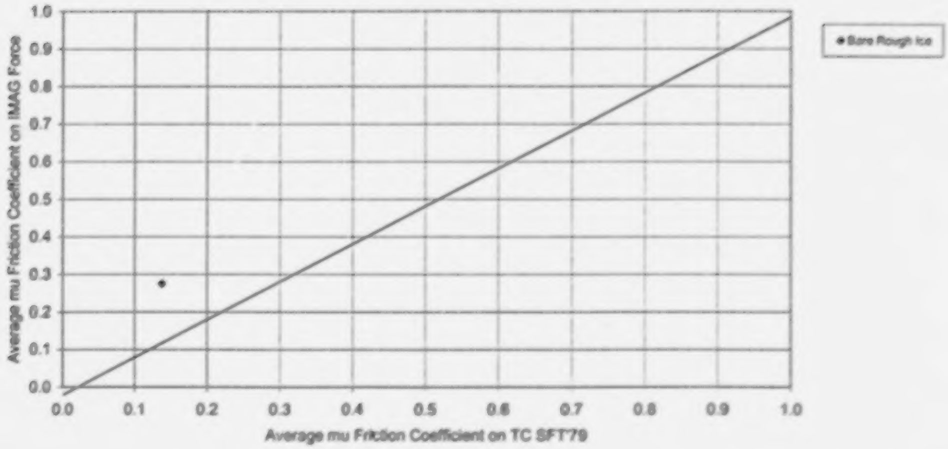
CORRELATION PLOTS: TC SFT'79 VS. IMAG FORCE



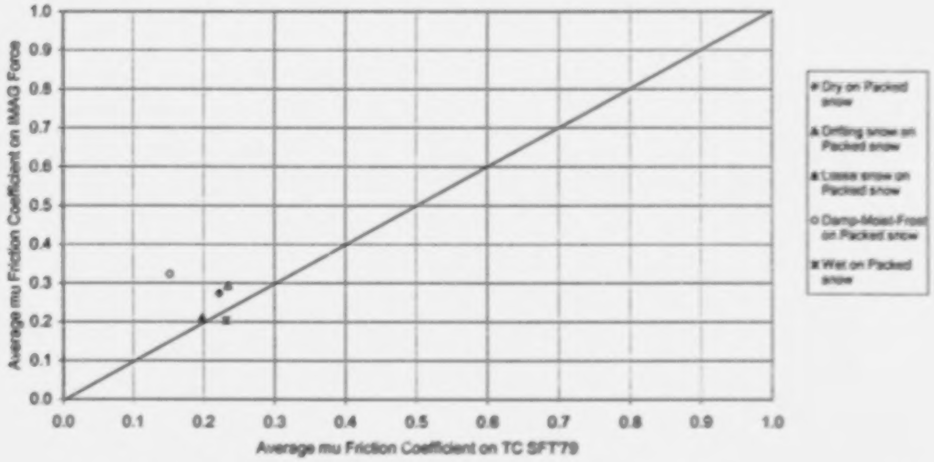
N-1: Correlation of TC SFT'79 to IMAG Force (Configurations 3 and 7) on a Pavement Base



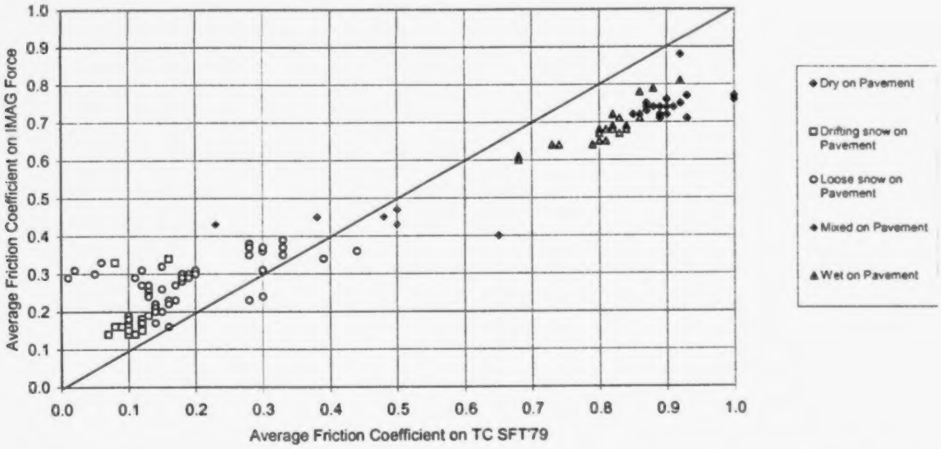
N-2: Correlation of TC SFT'79 to IMAG Force (Configurations 3 and 7) on an Ice Base



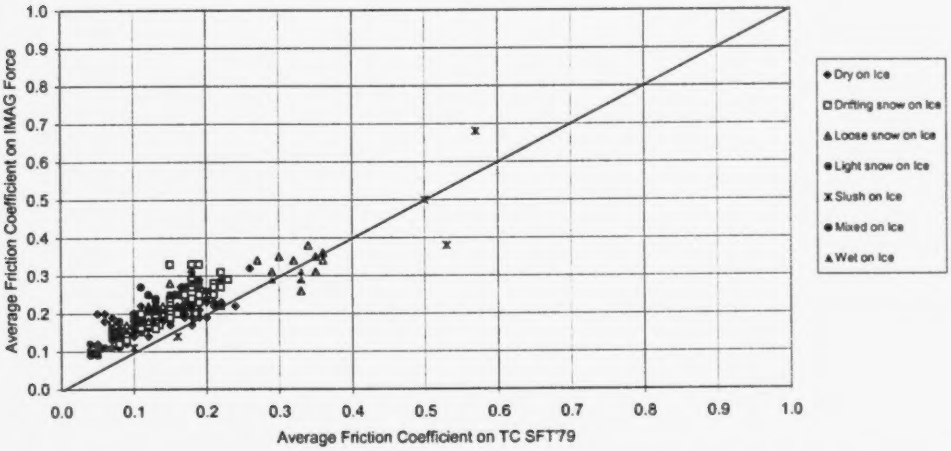
N-3: Correlation of TC SFT'79 to IMAG Force (Configurations 3 and 7) on a Rough Ice Base



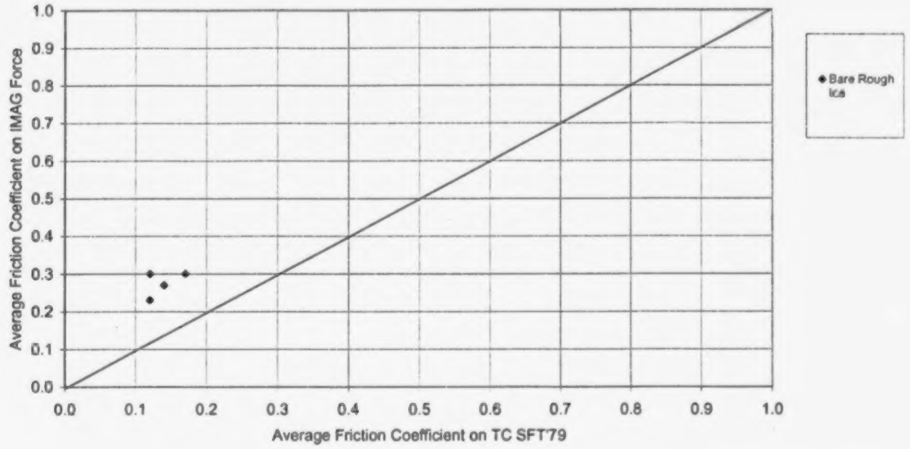
N-4: Correlation of TC SFT'79 to IMAG Force (Configurations 3 and 7) on Packed Snow



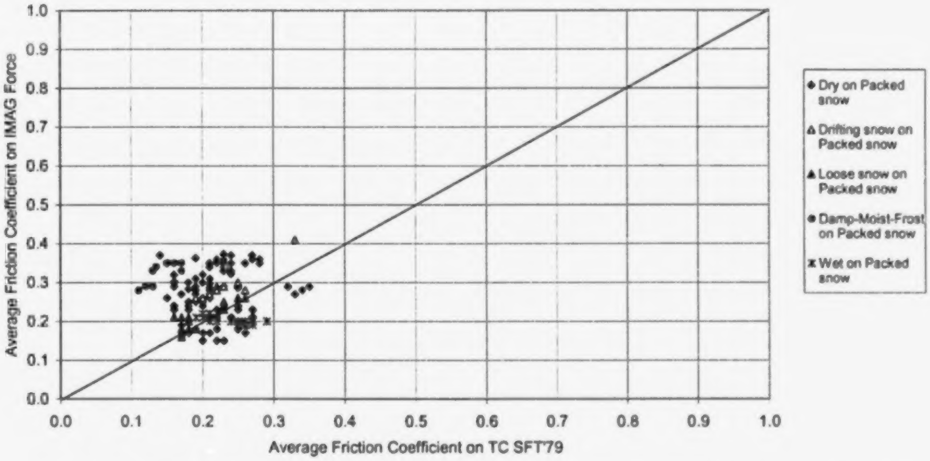
N-5: Correlation of TC SFT'79 to IMAG Force (Configurations 3 and 7) on a Pavement Base



N-6: Correlation of TC SFT'79 to IMAG Force (Configurations 3 and 7) on an Ice Base



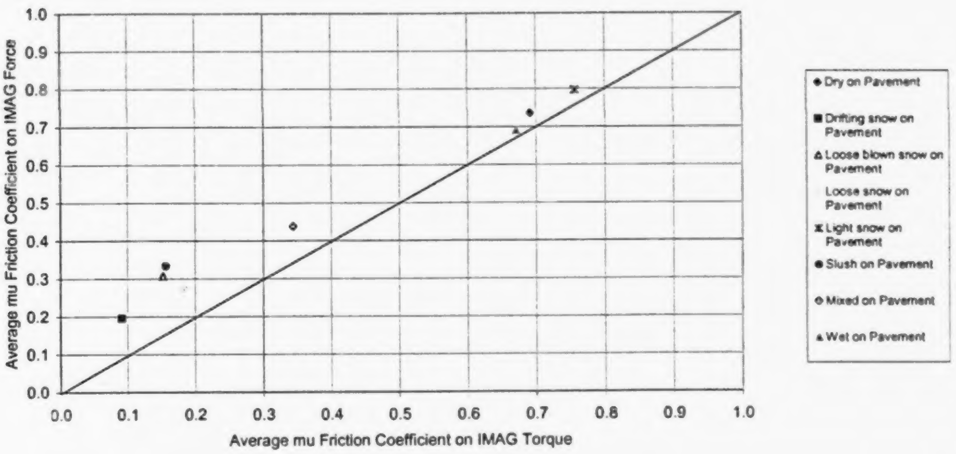
N-7: Correlation of TC SFT'79 to IMAG Force (Configurations 3 and 7) on a Rough Ice Base



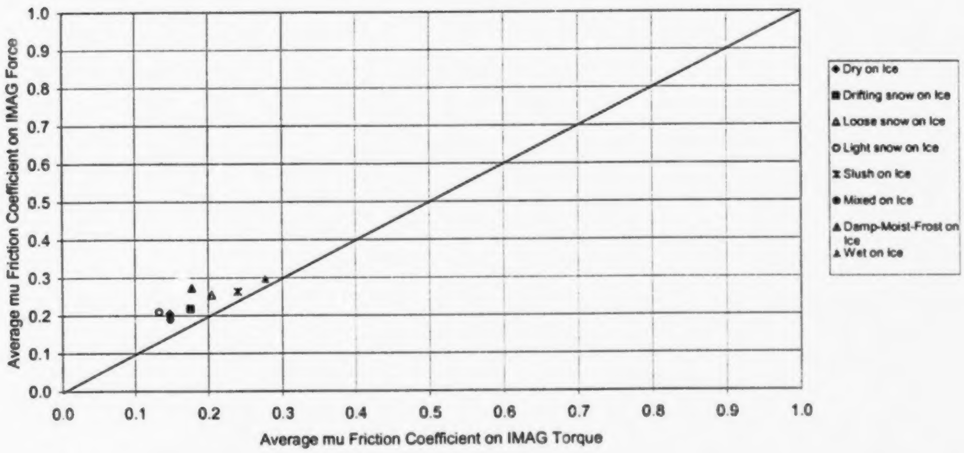
N-8: Correlation of TC SFT'79 to IMAG Force (Configurations 3 and 7) on Packed Snow

APPENDIX O

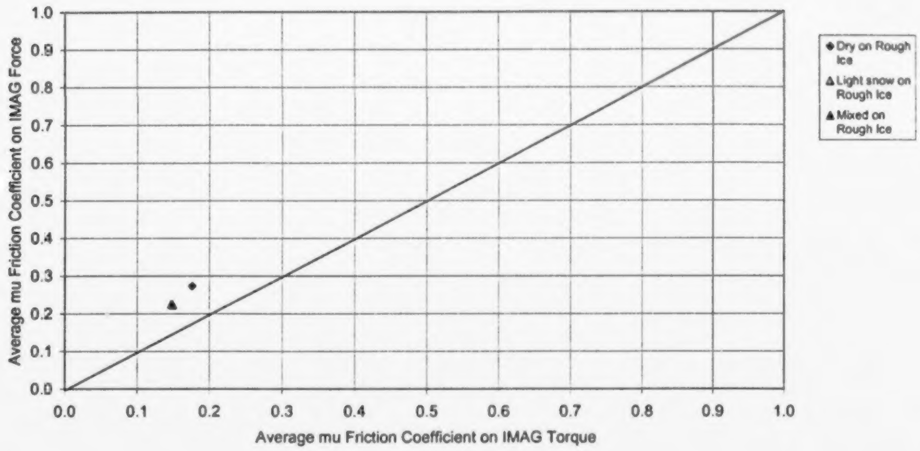
CORRELATION PLOTS: IMAG TORQUE VS. IMAG FORCE



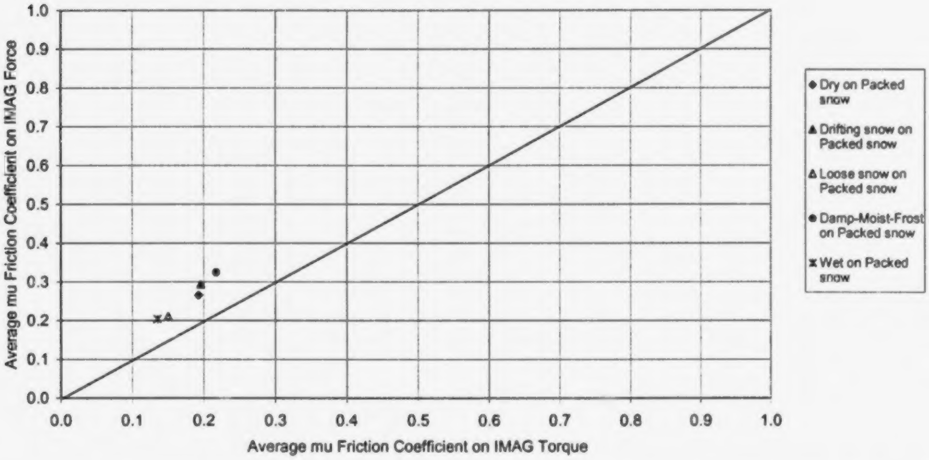
O-1: Correlation of IMAG Force to IMAG Torque (Configurations 3 and 7) on a Pavement Base



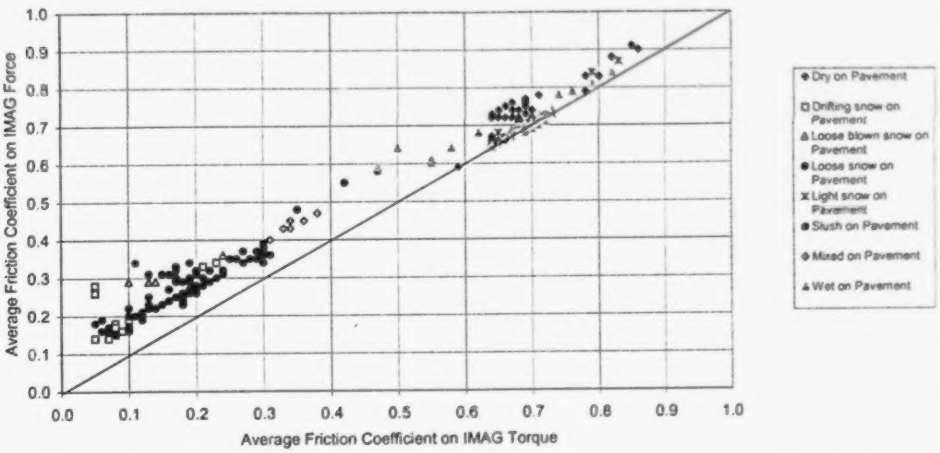
O-2: Correlation of IMAG Force to IMAG Torque (Configurations 3 and 7) on an Ice Base



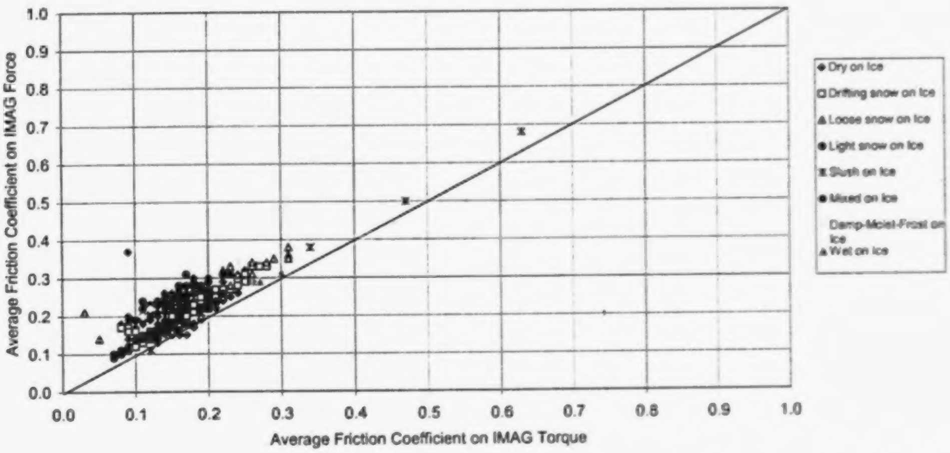
O-3: Correlation of IMAG Force to IMAG Torque (Configurations 3 and 7) on a Rough Ice Base



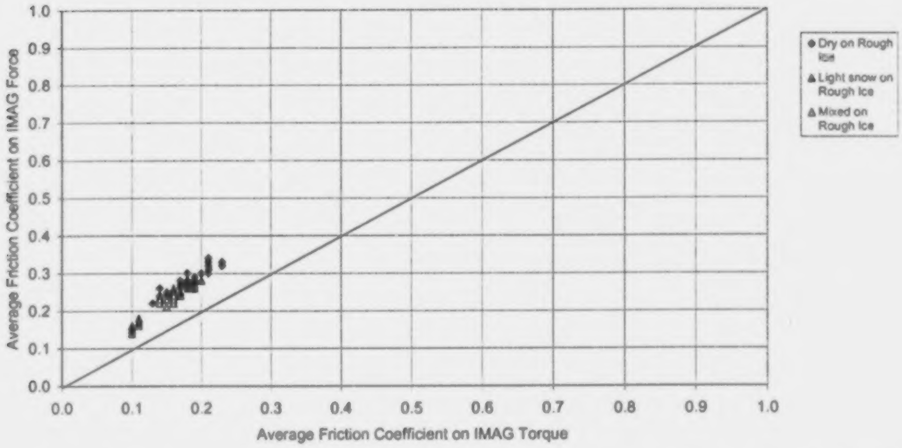
O-4: Correlation of IMAG Force to IMAG Torque (Configurations 3 and 7) on Packed Snow



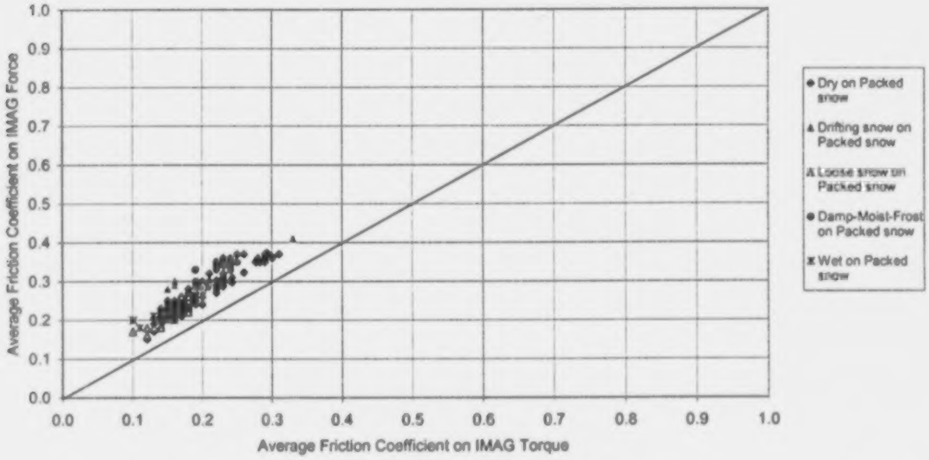
O-5: Correlation of IMAG Force to IMAG Torque (Configurations 3 and 7) on a Pavement Base



O-6: Correlation of IMAG Force to IMAG Torque (Configurations 3 and 7) on an Ice Base



O-7: Correlation of IMAG Force to IMAG Torque (Configurations 3 and 7) on a Rough Ice Base



O-8: Correlation of IMAG Force to IMAG Torque (Configurations 3 and 7) on Packed Snow

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